Technical Analysis and Characterization of Southern Cayo, Belize for Tropical Testing and Evaluation of Foliage Penetration Remote Sensing Systems

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Technical Analysis and Characterization of Southern Cayo, Belize for Tropical Testing and Evaluation of Foliage Penetration Remote Sensing Systems

This analysis was conducted by a scientific panel assembled by the United States Military Academy and USSOUTHCOM

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EXECUTIVE SUMMARY

The Department of Defense (DoD) has long recognized the significant challenges it faces in being capable of conducting military operations in wet tropical climates. First, successful operations require troops trained for sustained operations in the heat, humidity, and variable environmental challenges presented by wet tropical landscapes. This training must prepare troops understand the differences in conducting operations in jungles compared to temperate settings, the geographic domain for most US military training lands. The second critical point is that equipment must operate to its fullest capacity for sustained periods in these harshest of conditions. Finally, the US military must recognize that conflicts and operational requirements will continue to occur in these geographic areas; the evidence is overwhelming to confirm this fact. Since 1960 more than 75 percent of regional conflicts have had their roots in countries located within the tropics.

To meet the responsibility to conduct full spectrum operations throughout the contemporary operating environment, military equipment must be tested in harsh tropical conditions and servicemen and women must be trained within this demanding environmental setting. Many experienced military leaders have stated that training and conducting operations in the challenges of the tropics is the very best preparation for full spectrum operations. Leading units in the intensely demanding setting of the tropics prepares units for almost any challenge.

Under the terms of the Carter-Torrijos Treaty of 1977, the military mission in Panama was required to vacate the country by December 31, 1999. The DoD lost important capabilities with the closure of both the Army tropic testing facilities and Jungle Operations Training Center (JOTC) in Panama. As a result, DoD (with USSOUTHCOM's focused assistance) did not delay long to further restore these essential activities. To this end and as a primary example in finding alternative solutions, the US Army Test and Evaluation Command (ATEC), through its sub-element at US Army Yuma Proving Ground (YPG), developed a suite of alternative sites to support the tropical testing mission.

In 1998, YPG requested the assistance of the US Army Research Office (ARO) to convene an expert panel to undertake two related studies. The first study, ***"A Technical Analysis to Identify Ideal Geographic Locations for Tropical Testing of Army Materiel and Systems"*** (King et al., 1998), examined the Army tropical test mission to define the conditions that best provide the environmental challenges needed for tropical testing, at that time and into the 21st century. This work was groundbreaking in furthering how the Army considered the natural environment in testing and training. Before this effort, the Army viewed the tropical environment in terms of only basic climate measures, while failing to fully consider and define the complete environmental characteristics. This study characterized the climatic, physical, and biological characteristics defining

the ideal tropical test environment and identified regions of the world that best fit the composite specifications of an ideal tropical test environment. Sixteen regions of the world were identified that provide the requisite conditions of an ideal environment for tropical testing and training.

As a consequence of the initial study, follow-on studies examined locations in Hawai'i, Puerto Rico (King et al., 1999), Northeast Queensland, Australia (King et al., 2001), Panama (King et al., 2006a, 2007), and Suriname (King et al., 2006b). The specific charter for these follow-on studies was to evaluate specific areas within the 16 ideal regions searching for areas that possess the combination of environmental conditions defined in the initial study panel report as requisite to the testing and evaluation of Army materiel, equipment, vehicles, and weapon systems. The results included a regional analysis of the environmental setting for the areas, an environmental characterization of specific sites within each area, the rating of each site's capacity to support each component of the testing mission, and finally, conclusions as to the capacity to conduct tropical testing and training in these regions. Based on the findings from the six previous studies, the Yuma Proving Ground Tropic Regions Test Center (YPG-TRTC) has developed and is operating a testing facility at Schofield Barracks in Hawai'i and has conducted tests at several of the other sites characterized in the study process.

A primary finding of the tropic test study panel's early work was that a suite of sites would offer the best technical approach to replace the testing capacity lost with the closure of testing facilities in Panama (King et al., 1998, 1999). This conclusion was based on the absence of an ideal test site at any readily accessible location examined, where ideal is defined as a single location possessing all of the requisite environmental conditions. One of the key recommendations of the original study was that the Army pursues options for reestablishing test sites within the Republic of Panama. All of the work done to date has confirmed the value of Panama as a tropical test site location and discussions with the government of Panama have shown some willingness for cooperative efforts to conduct environmentally benign types of testing in Panama.

Over the last decade, seven separate reports were issued by the tropical test study panel, reporting the results of work conducted at 24 sites. The evolution of tropical testing to the suite of sites approach were compiled and integrated into a single document, which compared and contrasted all of the sites examined to date. This report, ***A Technical Analysis of Locations for Tropical Testing of Army Materiel and Opportunities for Tropical Training of Army Personnel*** (February 2009), summarized the environmental characteristics of the sites found to have testing value and made a comparative analysis between the twelve sites. It was intended to help the testing community select the best locations for each test and provide summary environmental data for test design. The original work remains important because each of those reports

contains environmental details that are critical to the testing community when they are selecting where to test.

Referencing this work, a concatenated study of a new, test site in Western Belize was deemed necessary for work being done there by USSOUTHCOM during 2010. A team of scientists was rapidly assembled to evaluated vegetation and geomorphology of a site at Southern Cayo, Belize, primarily in support of tropical testing and evaluation of foliage penetration remote sensing systems. This report represents those findings. Further work at the site may be necessary in order to support future testing of other equipment.

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CHAPTER I

OVERVIEW OF USSOUTCHCOM's TECHNICAL TESTING AND EVALUATION OF FOLIAGE PENETRATION REMOTE SENSING SYSTEMS

I.1. USSOUTHCOM – Science, Technology and Experimentation.

U.S. Southern Command's (USSOUTHCOM) mission statement reads as follows: "We are ready to conduct joint and combined full-spectrum military operations and support whole-of-government efforts to enhance regional security and cooperation." Supporting this mission statement is the commander's vision statement, which states that USSOUTHCOM is "a joint and interagency organization supporting US national security interests, and with our partners, improving security, stability, and prosperity in the Americas." To these ends, the USSOUTHCOM supports the testing of joint and interagency equipment, materials and concepts in its Area of Responsibility (AOR) with the office of primary responsibility being the Division of Science, Technology and Experimentation Office (ST&E). Support is provided in the form of providing and operational expertise test venues. The ST&E office works with the entire USSOUTHCOM enterprise, including components and Security Assistance Offices (SAOs) to provide support to these test activities.

The USSOUTHCOM Area of Responsibility provides ideal environments for the testing of military equipment and technologies. Additionally, excellent relations with partner nation government and militaries, close proximity to the U.S. and strong command support allow for excellent testing opportunities. The AOR has a variety of environmental settings that can be used, but of primary interest to most testing agencies is the tropical environment that is not found in the United States.

Over the years, USSOUTHCOM has sponsored many tests in the AOR via Joint Capability Technology Demonstrations (JCTD), service and interagency programs. These tests were executed with the full cooperation and participation of partner nations. Examples include the Foliage Penetration (FOPEN) Advanced Concept Technology Demonstration; Shadow Harvest multi-sensor demonstration and the A-160/FORESTER operational demonstrations. The technologies tested were primarily designed to "see through the jungle" and locate objects under the foliage. Among the technologies tested were Synthetic Aperture Radars (SAR), Ground Moving Target Indicators (GMTI), Light Detection and Ranging (LIDAR), Electro Optical (EO) and Infra-Red (IR) Systems. USSOUTHCOM assisted each of these activities with technical, operational, administrative and logistical support.

The USSOUTHCOM enterprise not only collaborates with service test agencies (i.e. U.S. Army Test and Evaluation Command and U.S. Air Force Research Lab), but with offices such as the U.S. Navy Office of Naval Research Global – Latin American Office, Chile; the U.S. Army International Technology Center – Latin American Office, Chile and the U.S. Air Force Office of Scientific Research, Brazil. These organizations seek first rate scientific collaboration in science and technology with partner nations. They are a readily available resource to USSOUTHCOM to continue fostering partnerships in the AOR and leveraging new ideas and concepts emerging from scientists in the region that can improve war fighter readiness. Interagency and university collaboration (i.e. Massachusetts Institute of Technology/Lincoln Lab and John Hopkins/Applied Physics Lab) are also critical in USSOUTHCOMs test and evaluation mission.

Previous editions of this series of environmental characterizations have been sponsored by the US Army Yuma Proving Ground. They cover analysis and environmental characterization for test sites in the "tropics," including but not limited to Panama, Honduras and Suriname. This edition was sponsored by both USSOUTHCOM J2 and ST&E office and was initiated and tailored in response to a requirement to establish a new test site in Belize for a specific test. Although written in support of one test, this technical analysis and characterization of the Southern Cayo area of Western Belize is valid for use in preparing future test activities.

In development of this analysis considerations were given to the effects of weather, terrain, foliage type, seasonal changes and surrounding biomass in Western Belize. The selected areas used in the development were visited by personnel who develop and /or operated sensors and analysts who interpret the data. This report allows for readers to gain a "similar experience" of the foliage and get a better appreciation of the challenge posed by foliage, temperature and moisture/precipitation.

I.2. Foliage Penetration Remote Sensing Systems and Purpose of Study.

The ability to detect and/or identify activity under dense foliage presents a challenge to current sensor systems. Describing this environment to system developers, operators and analysts also is a challenge. When asked system requirements for sensors that will test or operate in the Area of Focus (AOF), the default response is: "the system needs to be able to penetrate triple canopy." The term "triple canopy" means different things to different people and is not quantifiable. Additionally the term fails to take into consideration factors such as weather, terrain, foliage type, seasonal changes and biomass density.

As introduced in the previous section, the purpose of this study was to provide SOUTHCOM personnel with a definition of the foliage penetration (FOPEN) requirements for selected sensors, namely SAR and LIDAR and communication systems [such as planned for use on the Forrester / A-160 (see picture below)]. This definition and supporting technical data was provided to sensor developers and operators during the developmental stage or in the planning stages of a deployment into the AOF. To allow for future analysis and study, the research team collected data from various locations with representative foliage for the development of a mathematical model(s) and/or or technical description(s). Locations both away from and near stream and/or river systems were considered. Effects of various environments on ground and airborne sensor systems were evaluated. The goal of the document is to allow a non-technical person to gain a greater understanding of the challenge posed by foliage and for a technical person to use the information in system development or refinement.

Figure 1: A-160

Considerations were given to the effects of weather, terrain, foliage type, seasonal changes and surrounding biomass. Areas used in the development of this product can be easily visited by personnel who develop and/or operate sensors and analysts who interpret the data. Ultimately, this report allows for readers to gain a "similar experience" of the foliage and get a better appreciation of the challenge.

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CHAPTER II

CHARACTERIZATION OF TEST SITE

II.1 Physical Geography of Belize.

Belize is located on the Caribbean coast of northern Central America. It shares a border on the north with the Mexican state of Quintana Roo, on the west with the Guatemalan department of Petén, and on the south with the Guatemalan department of Izabal (Figure 2). To the east in the Caribbean Sea, the second-longest barrier reef in the world flanks much of the 386 kilometers of predominantly marshy coastline. Small cay islands totaling about 690 square kilometers, dot the reef. The area of the country totals 22,960 square kilometers, an area slightly larger than El Salvador or Massachusetts. The abundance of lagoons along the coasts and in the northern interior reduces the actual land area to 21,400 square kilometers.

Figure 2: Belize

Belize is shaped like a rectangle that extends about 280 kilometers north-south and about 100 kilometers east-west, with a total land boundary length of 516 kilometers. The undulating courses of two rivers, the Hondo and the Sarstoon, define much of the course of the country's northern and southern boundaries. The western border follows no natural features and runs north-south through lowland forest and highland plateau. Topographical features divide the Belizean landscape into two main physiographic regions. The most visually striking of these regions is distinguished by the Maya Mountains and the associated basins and plateaus that dominate all but the narrow coastal plain in the southern half of the country. The mountains rise to heights of about 1,100 meters, with the highest point being Victoria Peak (1,120 meters) in the Cockscomb Mountains. Covered with shallow, highly erodible soils of low fertility, these heavily forested highlands are very sparsely inhabited. The second region comprises the northern lowlands, along with the southern coastal plain. Eighteen major rivers and many perennial streams drain these low-lying areas. The coastline is flat and swampy, with many lagoons, especially in the northern and central parts of the country. Westward from the northern coastal areas, the terrain changes from mangrove swamp to tropical pine savannah and hardwood forest.

The interlocking networks of rivers, creeks, and lagoons have played a key role in the historical geography of Belize. The largest and most historically important river is the Belize, which drains more than one-quarter of the country as it winds along the northern edge of the Maya Mountains across the center of the country to the sea near Belize City. Also known as the Old River, the Belize River is navigable up to the Guatemalan border and served as the main artery of commerce and communication between the interior and the coast until well into the twentieth century. Other historically important rivers include the Sibun, which drains the northeastern edge of the Maya Mountains, and the New River, which flows through the northern sugar-growing areas before emptying into Chetumal Bay. Both of these river valleys possess fertile alluvial soils and have supported considerable cultivation and human settlement.

II.1.A Geology.

Belizean geology consists largely of varieties of limestone, with the notable exception of the Maya Mountains, a large intrusive block of granite and other Paleozoic sediments running northeast to southwest across the south-central part of the country. Several major faults rive these highlands, but much of Belize lies outside the tectonically active zone that underlies most of Central America. During the Cretaceous period, what is now the western part of the Maya Mountains stood above sea level, creating the oldest land surface in Central America, the Mountain Pine Ridge plateau (Figure 3).

The hilly regions surrounding the Maya Mountains are formed from Cretaceous limestone. These areas are characterized by a karst topography that is typified by numerous sinkholes, caverns, and underground streams. In contrast to the Mountain Pine Ridge, some of the soils in these regions are quite fertile and have been cultivated during at least the past 4,000 years. Much of the northern half of Belize lies on the Yucatán Platform, a tectonically stable region. Although mostly level, this part of the country also has occasional areas of hilly, karst terrain, such as the Yalbac Hills along the western border with Guatemala and the Manatee Hills between Belize City and Dangriga. Alluvial deposits of varying fertility cover the relatively flat landscapes of the coastal plains.

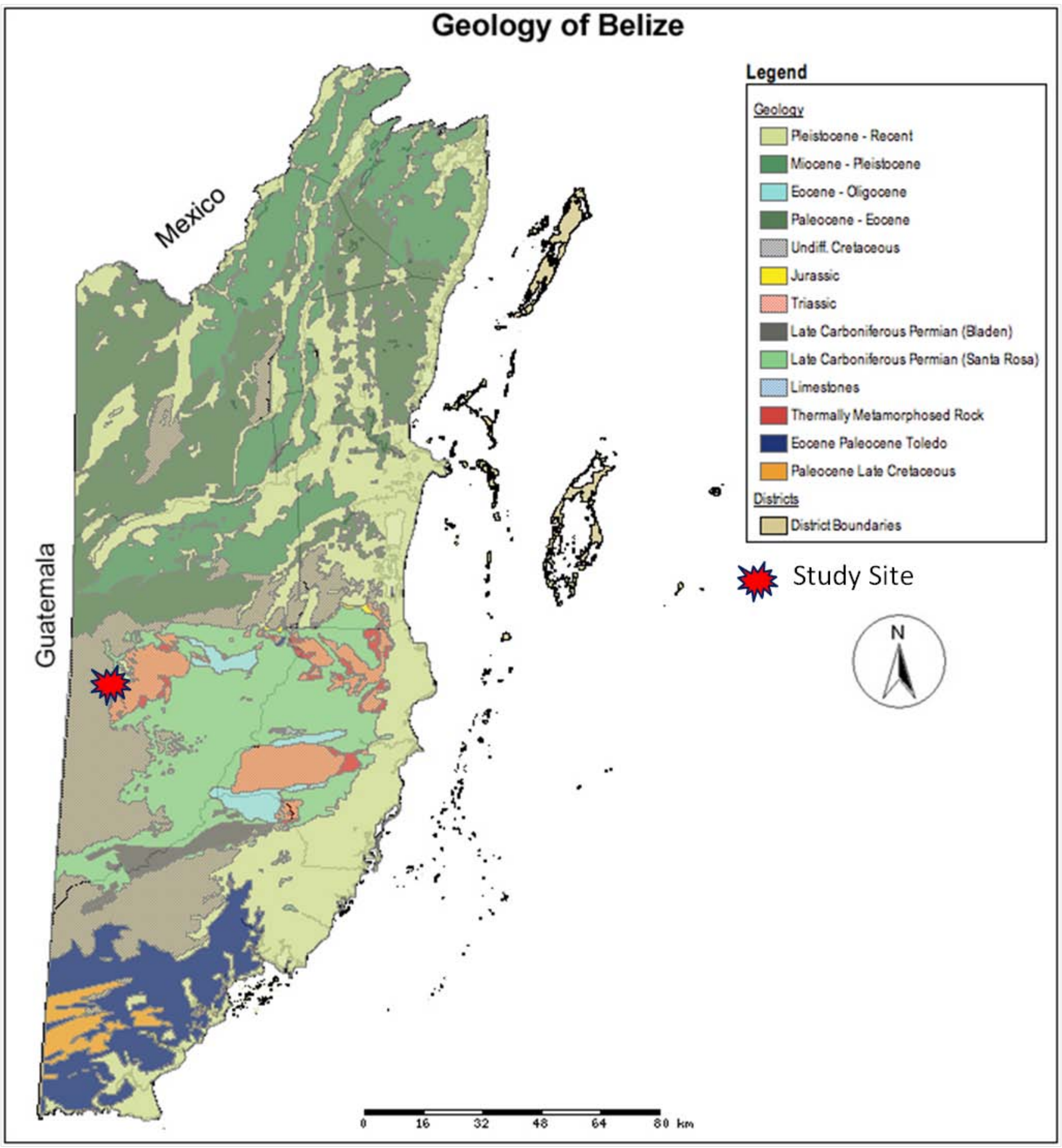

Figure 3: Belize's Geology

II.1.B Climate.

Belize has a tropical climate with pronounced wet and dry seasons, although there are significant variations in weather patterns by region. Temperatures vary according to elevation, proximity to the coast, and the moderating effects of the northeast trade winds off the Caribbean. Average temperatures in the coastal regions range from 24° C in January to 27° C in July. Temperatures are slightly higher inland, except for the southern highland plateaus, such as the Mountain Pine Ridge, where it is noticeably cooler year round. Overall, the seasons are marked more by differences in humidity and rainfall than in temperature.

Average rainfall varies considerably, ranging from 1,350 millimeters in the north and west to over 4,500 millimeters in the extreme south. Seasonal differences in rainfall are greatest in the northern and central regions of the country where, between January and April or May, fewer than 100 millimeters of rain fall per month. The dry season is shorter in the south, normally only lasting from February to April. A shorter, less rainy period, known locally as the "little dry," usually occurs in late July or August, after the initial onset of the rainy season.

Hurricanes have played key--and devastating--roles in Belizean history. In 1931 an unnamed hurricane destroyed over two-thirds of the buildings in Belize City and killed more than 1,000 people. In 1955 Hurricane Janet leveled the northern town of Corozal. Only six years later, Hurricane Hattie struck the central coastal area of the country, with winds in excess of 300 kilometers per hour and four-meter storm tides. The devastation of Belize City for the second time in thirty years prompted the relocation of the capital some eighty kilometers inland to the planned city of Belmopan. One of the most recent hurricane to devastate Belize was Hurricane Greta, which caused more than US$25 million in damages along the southern coast in 1978.

II.1.C Vegetation.

The vegetation of Belize is highly diverse by regional standards, given the country's small geographical extent (Seddon and Lennox, 1980). Situated on the Caribbean coast of northern Central America, the flora and vegetation have been intimately intertwined with Belize's history. The nation itself grew out of British timber extraction activities from the 17th century onwards, at first for logwood (*Haematoxylum campechianum*) and later for mahogany, fondly called "red gold" because of its high cost and was much sought after by European aristocracy. Central America generally is thought to have gained much of its characteristic flora during the "Great American interchange" during which time South American elements migrated north after the geological closure of the isthmus of Panama. However, few

Amazonian elements penetrate as far north as Belize and, in species composition, the forests of Belize are most similar to the forests of Guatemala and the Yucatan. The vegetation of Belize was first systematically surveyed in the 1930s with recent mapping projects identifying seven principal terrestrial and coastal categories of native vegetation (Figure 4). They include: (1) lowland broad-leaved forest; (2) lowland pine forest; (3) submontane pine forest; (4) submontane broadleaved forest; (5) mangrove and littoral forest; (6) seagrass beds; and (7) riparian shrubland. The lowland broad-leaved forest is a diverse forest type in Belize, now greatly reduced in extent by clearance for agricultural land. It includes such tropical tree species as *Simarouba glauca*, *Calophyllum brasiliense*, *Terminalia amazonia* and lowland savanna. The last of these (lowland savanna) is an important vegetation type in northern Belize, in which scattered trees occur in "short grass" (actually mainly sedges). Savanna is maintained as open vegetation by a combination of wet-season flooding, dry-season drought and fire. Typical trees here include: *Acoelorraphe wrightii*, *Quercus oleoides* and *madre de cacao Gliricidia sepium*. The lowland pine forest or pine savanna (open forest mainly) is composed of Pinus caribaea var. hondurensis with shrubs such as the rough-leaved "sandpaper tree" (*Curatella americana*). The submontane pine forest is composed mainly of *Pinus ayacahuite*, *Pinus oocarpa* and *Pinus rudis* together with some broadleaved species. The submontane broadleaved forest is the characteristic vegetation of the Maya Mountain massif above 500m. Typical species here include *Podocarpus guatemalensis*, *Swietenia macrophylla*, *Terminalia amazonia*, *Virola brachycarpa*, and the palm *Astrocaryum mexicanum*. The mangrove and littoral forest are ecologically important to the coastal cayes. Several species of mangrove are found including: red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*) and white mangrove (*Laguncularia racemosa*). In addition, the buttonwood (*Conocarpus erectus*) - although not a true mangrove - is often associated with mangroves in littoral forest. The seagrass beds found in sandy bays often have extensive mats of seagrass. There are several different types in Belize: turtle grass (*Thalassia testudinum* in the *Hydrocharitaceae*), manatee seagrass (*Syringodium filiforme* in the *Cymodoceaceae*), duckweed seagrasses (*Halodule* spp in the *Cymodoceaceae*). Finally, the riparian shrubland is a mixed vegetation of shrubs and small trees with grasses and sedges, found along watercourses. Typical species include *Schizolobium parahybum* and *Ceiba pentandra*. Loss of this habitat was one of the particular environmental concerns of building the Chalillo Dam on the Macal River.

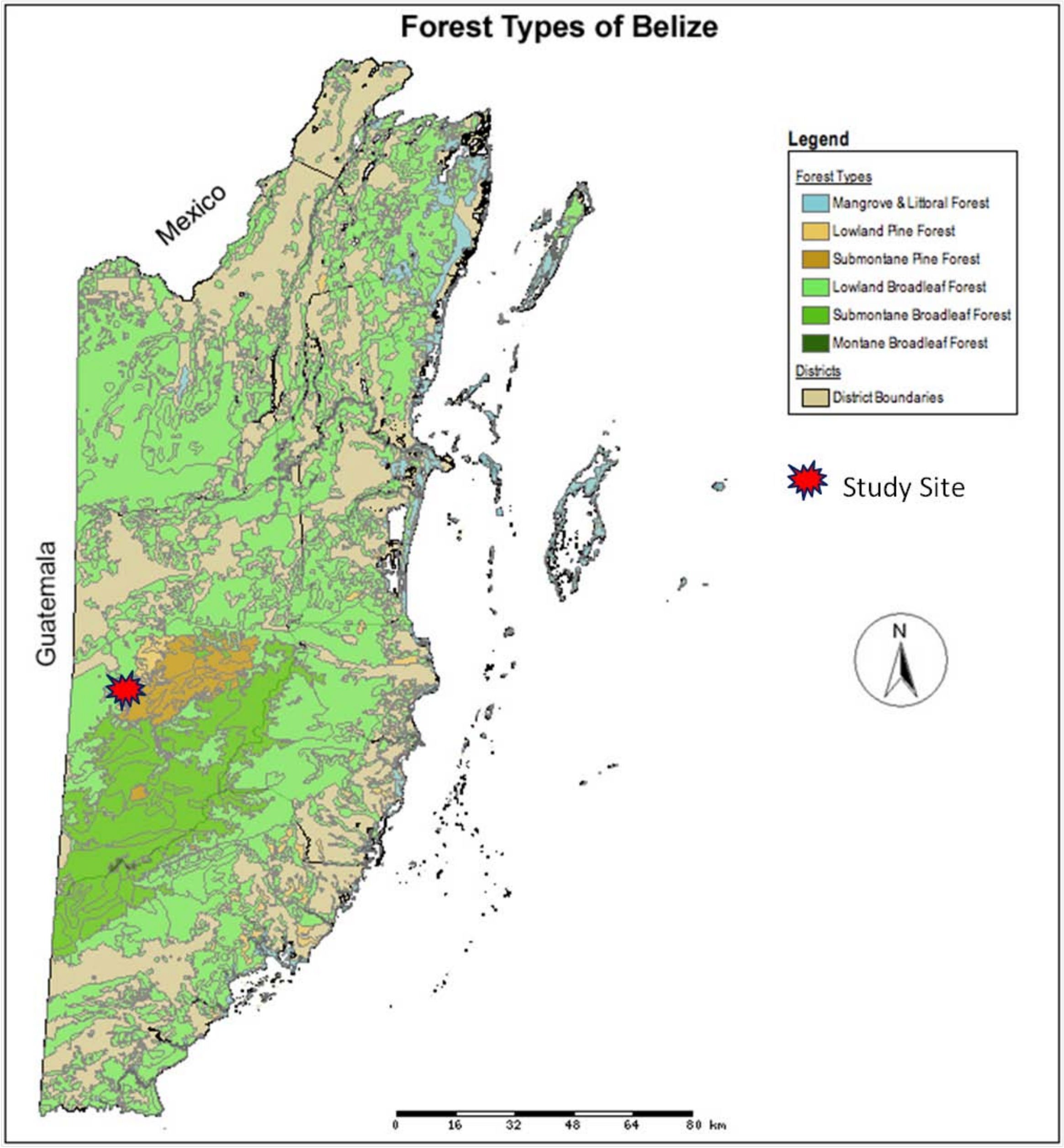

Figure 4: Belize's Vegetation

II.2. Southern Cayo Study Area.

The Southern Cayo Study Area is situated along the western border of Belize in what is generally named the Mountain Pine Ridge region just south of the town of San Ignacio. It is sometimes referred to as the Douglas da Silva region. Geographically, it is located south of the Tropic of Cancer, from 16 degrees, 30 min North latitude to 17 degrees 15 min North latitude and 88 degrees, 30 min West longitude to 89 degrees, 45 min West longitude. Interior to this general location, the

study area was further divided into six unique vegetation sites (V1-V6) and eight fluvial sites (F1-F8). These sites are shown visually on the image map and Joint Operations Graphic (JOG) map at Figures 5 and 6, respectively. The study area is generally described as lowland tropical, broadleaf rainforest. Although no weather station was present, rainfall is estimated to average about 2500 mm year in this area.

Figure 5: Image Map of Southern Cayo Study Area. If viewing digitally, click HERE to access the complete study area and mage in Google Earth. An interactive version of this image is found at Appendix 4.

Forests with rainfall exceeding 2000 mm/year are considered rainforests, or wet forests Thus, these forests are on the "dry" side of a designated rainforest. For comparison, the world's rainiest rainforests receive over 10,000 mm annual rainfall. Although rainfall and humidity are high year round, these tropical rainforests do have a dry season from December through May, transitioning to rainy season during June. During parts of the year when less rain falls, cloud cover is generally sufficient to keep the air moist and prevent plants from drying out. Many of the trees are evergreen and old leaves are shed, but not all at one time. Some trees are deciduous (shed all their leaves annually) during a part of the dry season. Only one tree species with leafless branches at the end of the dry season was observed. Seasons here are marked more by differences in humidity and rainfall than in temperature.

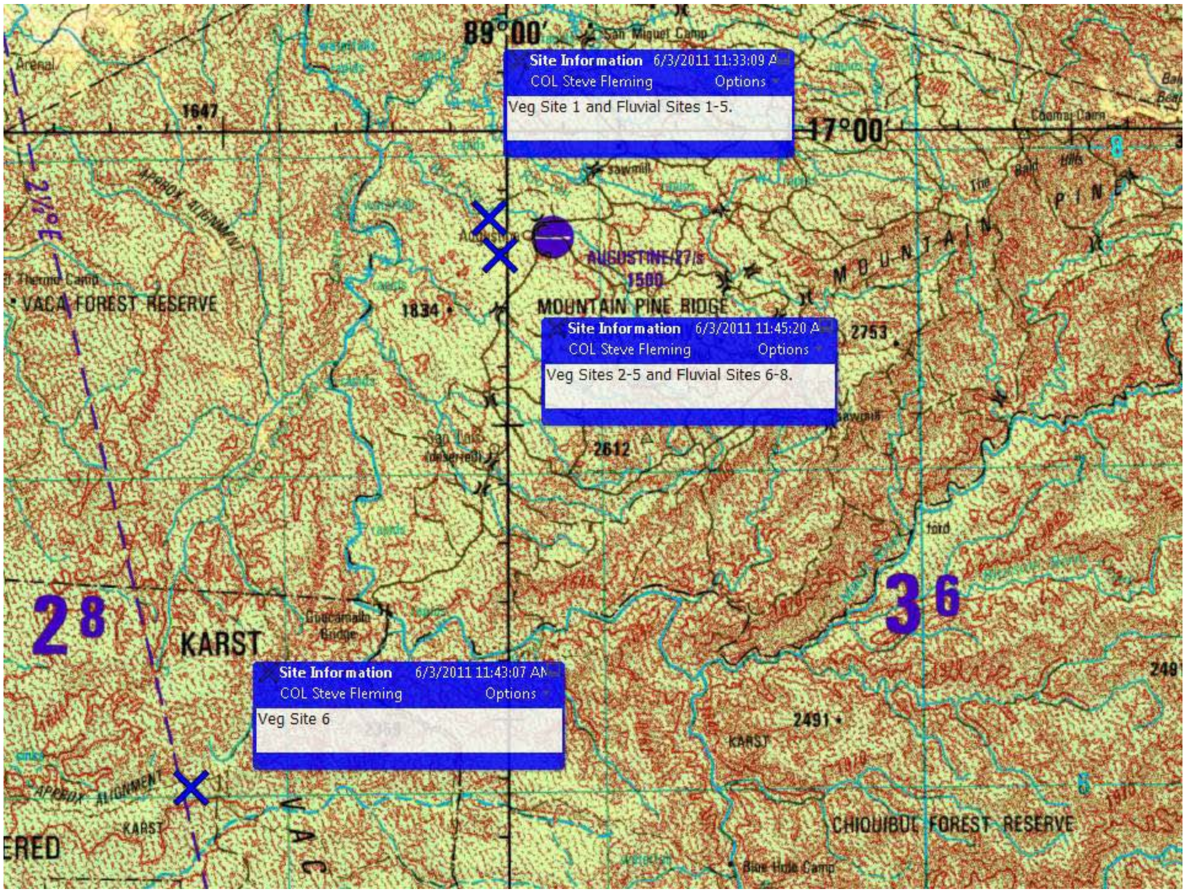

Figure 6: Joint Operations Graphic Map of Southern Cayo Study Area. A GeoPDF (interactive) version of this map is found at Appendix 4.

The topsoil is relatively thin and consists of weathered calcareous material over porous limestone karst, through which water drains quickly. Mature rainforests here are of lower stature than the lush, high-canopy lowland rain forests or montane cloud forests in the tropical forest belt further south in Central America, where annual precipitation is higher and weathered volcanic soils are deeper and retain water longer.

II.2.A. Vegetation of Southern Cayo Area.

Tropical rainforests by definition have more species of trees than any other biome in the world with 100 to 300 species counted per ha in some rainforests of Central and Southern America (Holdridge et al., 1974; Leigh, 1999). With an estimated 70% of the plants in a rainforest being trees, other plant forms include shrubs in the understory, vines or lianas and epiphytes such as orchids and bromeliads that are plants growing on other plants. There are typically four distinct layers of trees in a tropical rainforest: emergents, upper canopy, lower or subcanopy and forest floor. Widely spaced emergent trees are 30 to 70 m in height with large

umbrella shaped crowns and small, pointed leaves. Their trunks are straight and smooth with few branches. Finally, the trees have shallow roots and spreading buttresses to support the tall trunks. Upper canopy trees 18 to 40 m tall support numerous, small and leathery leaves to reduce water loss in the strong sunlight. The closed canopy effectively reduces light penetration to the lower canopy and forest floor. Lower canopy trees approximately 20 m in height, therefore adapt to filtered light conditions by increasing leaf size and thickness. In humid rainforests, epiphytes grow on the branches and trunks of trees in the upper and lower canopies. Over 2,500 species of rainforest lianas have been identified. These vines begin their growth as small shrubs on the forest floor but send out tendrils that wind around sapling trees and grow up into the canopy where there is more light. They rely on the trees they grow on for support thereby maximizing growth of photosynthetic leaves and stems rather than extensive trunks. The extremely high biodiversity of rainforests prevents mass die-off from disease or insects and ensures a rich diversity of pollinators.

There are over 750 tree species in Belize forests (Harris, 2009). The Southern Cayo site contained approximately 80% of these species. Hundreds of them have slick, elliptical-shaped leaves/leaflets with drip tips which may be entirely high overhead. Often, the trees have smooth bark, covered up and colored by lichens growing on the surface. Vascular plant species, including trees, are identified to species according to their flower structure. However, in this study area, only a couple species had a few remaining flowers at the tail end of the dry season when the sites were visited. Many trees have distinct leaves, fruits/seeds/seed pods, and stems/ branch tips (with leaf buds)/trunks/bark that allow identification in the absence of flowers—but even more "all look alike," especially when their leaves and branch tips are far out of reach.

II.2.A.1 Description and Identification of Species.

Mature Forest

Mature tropical rainforests are found in relatively undisturbed areas with stable and ideal growing conditions that support the survival of many plant species and growth forms. The intact forest canopy is composed of slow growing and self-replacing trees that maintain a consistency in forest height, structure and species composition (Harmon 2004). In the Belizean rainforest, vegetation includes: (1) tall, wide-crowned and scattered emergent trees species of the main canopy; (2) tall, un-branched and straight trunked trees within the canopy; (3) sub-canopy species both numerous and diverse with elongated crowns, branches extending the length of their trunks and lacking buttresses; and (4) the forest floor, supported by short herbaceous plants less than 1-m tall such as ferns, heliconias, liverworts and mosses.

As mentioned above in the description of the study area, the relatively thin topsoil of the study sites consists of weathered calcareous material over porous limestone karst. As a result, rapid water drainage in the karst geology creates drier edaphic conditions that can result in a slightly more xeric form of tropical rainforest with species adapted for water conservation and storage such as deciduous and compound foliage, waxy cuticles on leaf surfaces, wind dependent seed dispersal and fruiting periods synchronized to release seeds at the beginning of the rainy season (Harmon 2004).

Secondary Forest

Disturbances such as logging, storm damage and disease or insect infestation result in cleared areas that are regenerated by tree species adapted to grow in harsh environmental conditions with direct tropical sunlight, day and night temperatures that vary widely and powerful tropical rain that compacts the soil, runs off and causes erosion and declining layers of rich organic material. Species entering such disturbed areas tend to be hardy plants known as pioneering generalists that adapt to a range of conditions and create secondary forests, capable of surviving in well illuminated, dry and relatively infertile areas. These species may be found in small gaps created by overturned individuals within mature forests or throughout large areas cleared by logging, insects or disease. The forest canopy structure tends to be more homogeneous with fewer layers of canopy, fewer growth forms, less diversity and more even-aged trees with less varied crown shapes and sizes.

Administrative Data and Tabular Characteristics

As detailed earlier, the Southern Cayo Site is situated from 16 degrees, 30 min North latitude to 17 degrees 15 min North latitude and 88 degrees, 30 min West longitude to 89 degrees, 45 min West longitude. Interior to this general location, the study area was further divided into six unique vegetation sites (V1-V6). The specific location (in Universal Transverse Mercator [UTM] projection as well as Longitude & Latitude) of each of the observed vegetation sites is found in Table 1.

Table 1. Vegetation Site Locations
UTM Zone 16 (WGS84)

Vegetation Site Number	Easting	Longitude	Northing	Latitude
V1	286351	89 0 23.7 W	1878307	16 58 43.8N
V2	286793	89 0 8.5W	1877424	16 58 15.3N
V3	286426	89 0 20.9W	1877326	16 58 11.9N
V4	286343	89 0 23.6W	1877135	16 58 5.7N
V5	286115	89 0 31.5W	1877680	16 58 23.4N
V6	276660	89 5 44.8W	1860468	16 49 0.4N

Physical measurements of the vegetation at the six study sites were accomplished so as to accurately quantify the vegetation. Measurements of trunk size, trunk density and canopy height were made and recorded. This information by site is found in Tables 2 and 3.

Table 2. Vegetation Structure – Tree Size
Number of trees in diameter at breast height (DBH) size classes in 400 sq m area

Size Class	Vegetation Site Number					
DBH (in.)	V1	V2	V3	V4	V5	V6
16-20+	1	0	0	0	1	6
12-16	0	0	1	2	12	4
8-12	8	8	8	2	9	12
4-8	4	20	16	9	6	37
<4	Many	Many	Many	Many	Many	Many

Table 3. Vegetation Structure – Canopy Height
Height of canopy (feet)

Canopy Ht	Vegetation Site Number					
	V1	V2	V3	V4	V5	V6
ht (ft.)	35	40-45	35-40	40	60	55
# of Tiers	2	2	2	2	Stratified	Stratified
Comments	Subcanopy dense, even-aged canopy, many lianas at periphery nearest stream	Sparse subcanopy, even-aged canopy	Subcanopy of moderate density, canopy varied	Many epiphytes, subcanopy moderate, canopy varied, many gaps with palms	More mature forest near river, subcanopy moderate, canopy uneven and varied	Mature forest for this area, tall emergents, subcanopy moderate, canopy varied

In addition to these physical measurements, leaf area index (LAI) and diffuse non-interceptance (DIFN) was assessed using the LAI-2000. DIFN is the fraction of sky visible from below the canopy. The LAI-2000 collects radiation data using "fish-eye" optical sensors. At each site, measurements were made clear of canopy (“open skies”) and then below the canopy from five different light interception angles. From these measurements, LAI and DIFN were computed using a model of radiative transfer in vegetative canopies. Appendix 3 further describes this data collection method. Table 4 contains the DIFN measurements of the different vegetation sites.

Table 4. Vegetation Structure – Sky Visible Below Canopy
Percent illumination under the canopy

LAI-2000 Measurement	Vegetation Site Number					
	V1	V2	V3	V4	V5	V6
DIFN (%)	12.5 %	21.5 %	25.0 %	13.0 %	10.0 %	14.0 %

Finally, the iPIX Imaging System ® was used to collect and produce 360° immersive imagery products. From this, users are able to digitally explore the entire area where terrestrial images were collected (as if they were standing where the tripod holding the imaging device was placed). iPIX images can further be integrated into a GRID file (a format created by the National Geospatial-Intelligence Agency [NGA]) which allows for provisioning of detailed information about the imagery. iPIX files are ONLY VIEWABLE after installation of a free iPIX Viewer. The GRID files, however, are saved as an .exe file; they can be opened without installation of a special viewer. The purpose of collecting iPIX imagery and creating GRID files is to provide customers with an immersive visual representation of various test sites (in tropical settings). As with the LAI-2000, Appendix 3 further describes this data collection method. When viewing this as a digital report (either Adobe PDF ® or Microsoft Word ® document), interactive links are provided to these immersive images both in the next section of this report as well as in Appendix 4. The free iPIX Viewer (recommended) can be downloaded from the link provided HERE when viewing the digital version of this report.

II.2.A.2. Early Successional Secondary Forest Sites (V-1, V-2, V-3, V-4).

Site V-1 is mostly (75%) on a steep (40 degree), east-facing slope. A flatter toe slope is at the periphery, nearest the stream tributary to Rio Frio. A very early successional forest on the slope, this site has a thin canopy with trees mostly under 12 m height. This is the driest site we visited. There is one 45 cm DBH mahogany tree remnant from a former forest. The canopy and subcanopy more or less blend. Leaves are all small, except for the occasional *Elaeagia* with huge leaves. Sufficient light penetrates through the canopy to support a subcanopy of thick, small stems (<6 cm) and tangles of spiny *Smilax* vines that make walking difficult. The subcanopy also has bull horn acacia (*Acacia cornigeria*) with twice compound leaves and tiny leaflets, and the swollen, sharp thorns that harbor the stinging attack ants. Overall, the exposed subcanopy up on the slope does not make walking easy. One might disparagingly call this area "successional trash." The toe slope area at the northeast edge of Site V-1 near the tributary is more humid, with deeper alluvial soil. Water drainage here is slower; and thus the area supports taller trees with lianas, climbers (mostly herbaceous *Philodendron* vines) with large leaves, and some epiphytes. This is the "jungly" section of Site V-1. The canopy is uneven and 90% closed (see Figure 7). Light penetrates to ground level throughout Site V-1. The ground is 60% to 80% covered with dead leaves. Walking is more pleasant and possible in the jungly section.

Figure 7. Upward facing photo from V-1.

Sites V-2 and V-3 are on gently sloped (2-4 degree) uplands, not in close proximity to streams. These two sites are "type specimens" of young (very early successional), secondary rain forest. They have been recently logged, and a secondary forest perhaps 15-18 years old is re-growing. Judging from the tree stumps and cull trees left behind following the clearcut, these sites previously had been mature mahogany/tropical hardwoods forest similar to the forest at Site V-6 (described later). The canopy is 95% closed, and mostly composed of very even-age, even-height trees, 11-13 m (to 15 m in places at Site V-2), with small boles mostly under 10 -15 cm (up to 15 - 20 cm maximum); many are only 5 cm or less DBH and packed together like matchsticks on end in places. Tree species are stratified into only two layers: canopy and subcanopy (see Figures 8 and 9). Subcanopy at Site V-2 is sparse. All trees have small to medium leaves or leaflets except one subcanopy species, the ear lobe tree, which, in this short stature forest, occasionally reaches into the canopy. Young cohune palms (the upside down feather dusters without noticeable trunks yet) soar to 7 m and block views. Occasional older, taller trees remain left over from the logging, especially at Site V-3, probably because they were too small in diameter at the time and/or had poor form. Most of these are mahogany trees 20-25 cm DBH and up to 17-m height. They are taller than the rest of the quite level canopy top, but are not the true "emergents" of a mature, stratified canopy structure. Evidence of

past logging: old tree trunks on the ground and old stumps rotting but still discernable; many coppiced trees; slanted trees once pushed over and now with secondary, straight "sprout" trunks which have grown taller than the original trunk; and trees which are former stump sprouts, growing close together around the periphery (reminiscent of a mushroom fairy ring) where very large, now rotted stumps were. Species composition differs from the former mature forests at these sites. Some are trees, saplings, stump sprouts, or grew from the seed bank left from the former forest. Tree species that grow fast from recently cut stumps with an established root system get a jump start on seedling trees that had to sprout and establish a new root system. Many species are invasive, early successional species—opportunists-- that claimed the clearing and are growing fast, but will eventually be overtopped and replaced. There is a well developed shrub layer with small leaves at Site V-3. Palms having large, fan-like leaves are common in the shrub layer at both V-2 and V-3. Although the canopy is closed, sufficient light penetrates through the small leaves to support the shrub layer. There are few lianas, no climbers, and a few small epiphytes. There are no dense vine thickets in the low shrub layer. The ground layer is 90% covered by dead leaves.

Figure 8. Upward facing photo from V-2.

Figure 9. Upward facing photo from V-3.

Site V-4 is a secondary forest we estimated at 12-15 years old or less, on a flat terrace near a stream tributary to Rio Frio. This is the most humid of the four secondary forest sites we visited. Alluvial topsoil is deeper here than at the upland and slope sites. The canopy is uneven, +/-13 m height. Most boles are under 13 cm DBH. Several trees remnant from the former forest are 18 m height. They are taller than the rest of the canopy, but are not the true "emergents" of a mature, stratified canopy structure. Canopy is thin enough to allow light penetration to ground level; only about 75-80% canopy closure (see Figure 10). There is no evidence of large trees having been logged which caused wondered as to why the canopy was so relatively open. Small epiphytes (bromeliads) grow upon the tree trunks. This site has the most light penetration of the sites we visited, hence the epiphytes—but these are not the large, lush epiphytes that would grow in cloud forest conditions. Fan leaf type palms are common in the subcanopy and tall shrub layer. The ground layer is dead leaf and low herbaceous cover. Walking is easy with the view open.

Figure 10. Upward facing photo from V-4.

II.2.A.2. Mature Forest Sites (V-5, V-6).

Sites V-5 and V-6 are mature forests, probably not cut in over 50+ years (although there was evidence of some selective cutting) and having a high diversity of tree species. No trees are dominant and the variety is great. These forests are notably *stratified*, or *layered*, from ground level to the top. In general, stratification results because the numerous and varied species of trees grow to characteristic, different maximum heights. The canopy is uneven in height in part because trees are different ages; some are dying, and there is continual new recruitment. Upper layer *canopy* trees are about 16-19 m, with straight boles mostly unbranched up to the crown. All the canopy trees here have characteristically thin, small to medium size leaves or leaflets, mostly smaller than 4 cm x 11 cm. Most leaves or leaflets have an elliptical shape which often ends in drip tips, well adapted for shedding water and moving in wind. There are no broad leaves with lobes, such as many species of oak or maple leaves, that would be characteristic of temperate forests in the eastern United States. Leaf structure and thickness of the internal layers have important effects on electromagnetic spectral reflectance and absorption. Referring to the diagrammatic

leaf cross-section in Figure 11, leaves have an upper palisade mesophyll (meaning, "middle of leaf") layer of photosynthetic cells packed tightly on end. Beneath the palisade layer is a spongy mesophyll of loosely packed cells and air spaces where water and gaseous exchange occurs. No trees in these tropical wet forests have very thick, leathery leaves with a thick spongy mesophyll, or leaves with a heavy, waxy outer covering (cuticle), as would occur in drier forests and woodlands where leaf structure is adapted to conserve water. Chicle (= sapodilla, zapote, sapote) (*Manilkara zapota*) and Copal trees (*Protium copal*) are common trees here that are somewhat an exception, with their glossy, dark, evergreen leaves that tend toward leathery.

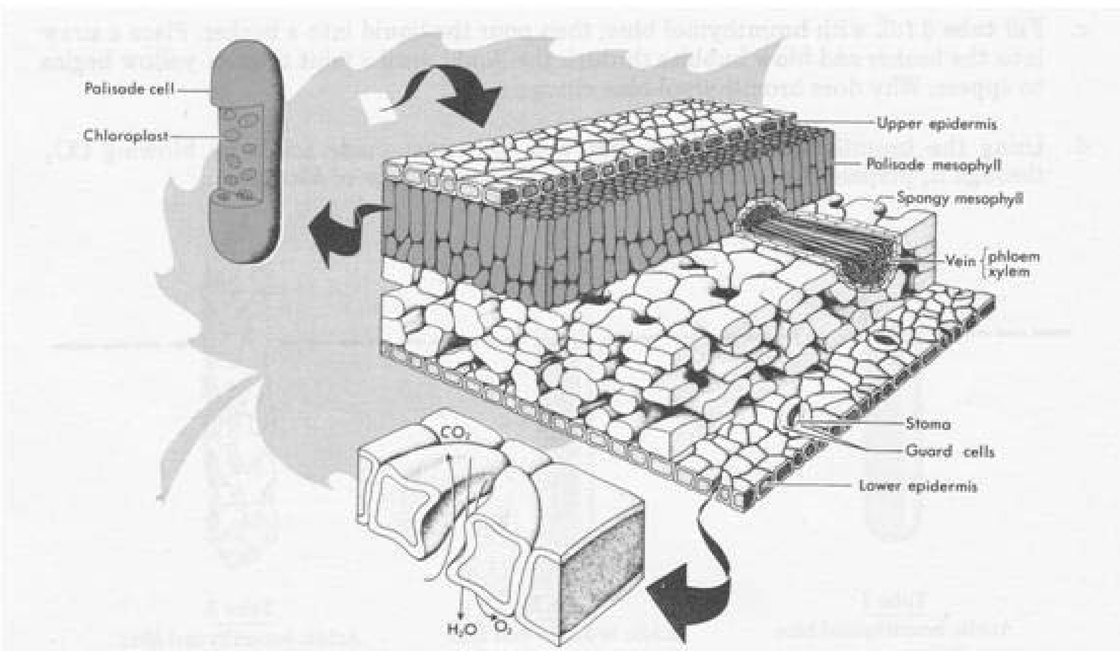

Figure 11. Diagrammatic leaf cross section (notice that cells in the mesophyll have numerous chloroplasts) (Copyright C. Benjamin Meleca, Phyllis E. Jackson, R.K. Burnard and David M. Dennis, *Bio-Learning Guide 2nd ed.* Burgess Division of MacMillan. 1975).

Water content of leaves also affects electromagnetic spectral reflectance and absorption. Water content will vary with air temperature and relative humidity, and of course, will vary seasonally. Water content would be an important consideration for applications using microwave radiation, for example. Further information about leaves: Many of these tropical trees have compound, or doubly compound leaves, so what we may call "leaves" are actually the leaflets arranged along each side of a long, common axis (the rachis). Doubly compound leaves [eg., leaves of Quamwood (*Schizolobium parahyba*)] are most often large and fern-like, with the individual leaflets being tiny. Some trees [eg., Ceiba (*Cieba pentandra*)] have

palmately compound leaves with the leaflets radiating out from a central point like fingers from the palm of the hand. The important point about leaf size is, even when the canopy is 90-95% closed, some light does filter through these small leaves of the upper strata, to reach the larger and larger leaves on trees in lower and lower strata, and finally, some light reaches the ground surface in a mottled pattern of light and shade. This is not dark jungle floor. During the time we were there a constant breeze changed the pattern of leaves that would block light and other electromagnetic radiation. Site V- 6, especially, has scattered canopy emergent trees about 22-m, with broad, rounded crowns that soar above the rest of the canopy. Some of the canopy species and all the emergent species have trunks buttressed at the bottom; the older the tree, the greater the buttress for that species. Leaves and leaflets of emergent tree species were all small with a shiny surface (thin, waxy cuticle), well adapted to withstand full sun and wind. All of them allow electromagnetic radiation to filter through. Notable canopy and emergent species in these forests are: Mahogany (*Swietenia macrophylla*), the national tree of Belize; and Cieba (pronounced 'say-ba') or Kapok), the Mayans' "Sacred Tree of Life" and also the national tree of Guatemala. Santa Maria (*Calophyllum brasiliense*) with its dense crown, is in the canopy and often is an emergent. Quamwood is a spectacular emergent species with those giant, fern-like leaves and crowns towering above the canopy like parasols. Cedro (*Cedrella odorata*) in the canopy and may also be an emergent. Several of the many other canopy species are Fiddlewood (*Vitex gaumeri*), which has unusually long leaflets, 6-22 cm; Chicle or Sapodilla (=Zapote or Sapote) with its hard and durable wood, tough 10 cm leaves, and gummy resin which is famous in Wrigley's chewing gum and chiclets**;** Nargusta (*Terminalia amazonia*); Ironwood or Tamarindo (*Dialium guianense*); and Ramon (*Brosimum alicastrum*). At Site V-6, some amazingly large Gumbo limbo (*Bursera simaruba*), 40-45 cm DBH, grew into the canopy. These plants were in the subcanopy at both sites and are more often an indicator of a youthful forest, though they also occur in primary rain forest. The top of canopy at both sites was characteristically of uneven height owing to gaps, to emergent trees, and to the age range of individual trees in the population.

There was some occurrence of canopy gaps. Mortality from old age, disease, wind throw, etc., left natural gaps (light openings) in the canopy where new individuals capable of fast growth filled the vacancy as they competed for a place in the sun. The newcomers in gaps were rapid growing, "light-loving" pioneer species such as *Cecropia* (Cecropia spp.) trees with their gangly growth habit and unmistakable, huge "umbrella" leaves 30-50 cm across and (palmately compound) with 9-11 fat, finger-like leaflets; Negrito (*Simarouba glauca*), and cowfoot (*Piper auritum*) tall shrubs. They were also the established individuals that had been biding their time in the shade until they could snatch an opening for canopy status.

Several layers of subcanopy *trees*, in layers not distinctly separated from one another, grow at various heights beneath the canopy under conditions of ever decreasing light. One tree species common in the mid-subcanopy, the ear lobe tree

(*Elaeagia auriculata*) has exceptionally large leaves (15-17 cm long, though we saw leaves 25 cm and more on juvenile trees). Poisonwood (*Metopium brownei*), Horseballs (=cojotones) (*Stemmadenia donnell-smithii*), Negrito (*Simarouba glauca*), Hog Plum (*Spondias mombin*), Polewood (*Xylopia frutescens*), Prickly Yellow (*Zanthoxylum kellermanii*), Salmwood (*Cordia alliodora*) and Gumbo limbo are some of the many species we saw mainly in the subcanopy. Others were the already mentioned canopy species which pass through the layers of subcanopy on their way upward. The subcanopy is ever changing.

Palms are common in places in the subcanopy layers and tall shrub layers. The palms block views and should provide some cover for human movement through these forests. Massive cohune palms (*Orbigyna cohune,* = *Attalea cohune*) with their long, very dark green, plume-like fronds ("leaves") up to 10 m are prominent in the subcanopy. Picture mature cohunes as giant, upside-down, dense feather dusters. Old cohunes have grown trunks beneath the base of their leaves and some reach a height near the top of the sub-canopy. Young cohunes in the low subcanopy have not yet developed a noticeable trunk, so their majestic fronds appear to be erupting straight from the ground in a heavy clump. Cohune palms were especially numerous at Site V-5. A solitary palm species with large, flat, fan leaves, the Give-and-Take palm (*Crysophila stauracantha*, formerly *C. argentea*) most famous for its vicious, downward-pointing spines along the trunk, grows to 4-6 m in the subcanopy.

The tall shrub "understory" layer (1-4 m) at both sites is characterized by palms with flat, fan-like leaves oriented horizontally toward the sun. These palms (e.g. Bayleaf palms, *Sabal maurtiiformis;* and Xate and/or Fishtail Palms*, Chamaedora* spp. *)* range from occurring individually to growing in clusters 3-4 m in diameter. Several broad-leafed, herbaceous plant species grow amongst the understory palms in the low shrub layer. Woody shrubs are scattered. The low shrub/tall herbaceous *layer* is sparse. The ground layer is mainly dead leaf litter, with sparse low herbaceous vegetation. Human movement through these mature forests is not difficult, mainly some vines and palms to avoid. *Lianas* (hanging vines) are common in places, stretching from canopy where their leaves are, down to ground level. Most of the lianas in the canopy have small leaves, with woody stems hanging straight to the ground like dangling ropes, dense in some places. Some have numerous aerial roots not reaching the ground. The *climbers* are climbing herbaceous or woody vines attached to tree trunks. Climbers are the more shade tolerant species adapted for life in the sub-canopy. The most prominent of them are broad-leafed, herbaceous species such as *Philodendron* spp., with large leaves aimed broadside toward the sun. Climbers are not "everywhere" as they would be in a cloud forest, but where they occur, they intercept electromagnetic radiation. There are also tangles of thick, woody vines, mostly grape vines, growing in the low and tall shrub layers, and reaching into subcanopy levels. *Epiphytes* (*epi* = "upon," *phyte* = plant") are non-parasitic, green plants that grow upon other plants, to reach a place

in the sun. They trap all the nutrients and water they need from the humid air and detritus on high. Epiphytes are present but not numerous, and the species at these two mature forest sites are not large. Most are bromeliads, that is, members of the pineapple family Bromeliaceae. Think of 1-year and 2-year old pineapple plants growing in trees. Epiphytes here are not massive and not "everywhere" as they would be in a cloud forest where humidity is high all day, every day of the year, but where epiphytes occur, they will intercept electromagnetic radiation.

Site V-5 is at the sloping edge of a constantly humid river ravine. Soil here appears to be somewhat richer and deeper than at upland Site V-6. Canopy is uneven, with more gaps and openings than "typical." There are several scattered giant canopy and emergent trees, and large cohune palms. Palms in the low subcanopy and tall shrub layers are numerous (more than at Site V-6). The openings and uneven canopy may be a result of past selective logging of mahogany and other large timber. We would expect more giant, emergent trees and fewer cohunes at this rich site if there was selective removal. The forest floor is open enough that human movement is not difficult. All of Site V-6 is upland, and has a more or less typical canopy of even height, with emergents and gaps. Site V-6 is the best "type specimen" rain forest site of those we visited. Canopy closure is 90-95% (see Figures 12 and 13).

Figure 12. Upward facing photo from V-5.

Figure 13. Upward facing photo from V-6.

II.2.B. Geomorphology of Southern Cayo Area.

Similar to the vegetation collection detailed previously, two field areas were studied. They were both situated along the western margin of the Mountain Pine Ridge province and the eastern margin of the Vaca Plateau (see Appendix 3 - physiographic and geologic maps) along tributaries to the Macal River, which separates the two physiographic provinces. Area 1 (Rio Frio sites) is on the western fringe of the Mountain Pine Ridge, whereas Area 2 is on the eastern fringe of the Vaca Plateau. The Mountain Pine Ridge province is composed of late Paleozoic granites that have been unroofed of sedimentary rocks (sandstones, mudstones, and limestones) and dissected by fluvial erosion, resulting in moderate to high relief topography. Bateson (1972) dated granite in Mountain Pine Ridge at 280-390 million years old, and it is believed to be the oldest rock that outcrops in Belize. These granites constitute the structural basement rocks of the "Maya block" in Belize, Guatemala, and the Yucatan of Mexico (Donnelly, 1990; Bundschuh and Alvarado, 2007). The Vaca Plateau is a limestone karst platform that is mostly developed on Cretaceous age (144-65 mya) limestones and has been dissected by fluvial and karst

processes, resulting in moderate to high relief topography with steep hills and intervening valleys with underground karst drainage (Figure 14).

Figure 14. Fluvial Geomorphology in Belize (streams and caves).

II.2.B.1. Area 1 (Rio Frio) Description.

Area 1, near Augustine/Douglas da Silva, stradles the western edge of the Mountain Pine Ridge province at its contact with the Vaca Plateau. Study sites are situated along Rio Frio and its tributaries at about four or five kilometers southeast of Rio Frio's confluence with the Macal River (see Appendix 3 - physiographic map), which is also designated the "Eastern Branch" on some maps. Limestone occurs on the eastern fringe of the Vaca Plateau and nonconformably overlies the basement granite of Mountain Pine Ridge. In Area 1 the contact between the limestone and underlying granite occurs in the hillsides along the river valley margin at elevations barely above the level of Rio Frio. In fact, the first site surveyed was immediately downstream of the northern entrance to the Rio Frio Cave, which is a natural tunnel through which Rio Frio flows for about 100 m before the river meets daylight again. The limestone-over-granite contact is readily visible in lowest levels of the cave walls only a few meters above water level. The Rio Frio is a bedrock channel floored by granite with numerous reaches where granitic sand, gravel, cobbles and boulders constitute the most of the clastic bedload materials. Indeed, the majority of the Rio Frio's drainage basin appears to erode only granite, whereas the limestone only

appears to constitute this western end of the Rio Frio drainage basin along the contact between the Vaca Plateau and Mountain Pine Ridge. Many reaches of Rio Frio and its tributaries flow over waterfalls, cascades, and rapids formed on the most resistant outcrops of the basement granite. Surveyed parts of the Rio Frio were about 5 to 10 meters wide and the surveyed tributary sites ranged from about 1 to 5 m wide.

All study sites in Area 1 were places where the bed of Rio Frio and its tributaries were scouring the granite, and as such the stream and river beds were in themselves suitable trails. Most of the channel banks were formed in unconsolidated sediment or scoured in bedrock. However, in a few interesting cases (F-6 and F-8) the banks of the stream channels were composed of tufa, which is a hardened carbonate mineral that precipitates from freshwater seeps and springs. It appears that carbonate-saturated waters seeping through the limestone are forced to move laterally into the streams at the limestone/granite nonconformity, and these carbonate-saturated waters thus precipitate as tufa on the stream banks. Such indurated stream banks should serve as excellent reflectors for radar and LIDAR emissions.

Soils in Area 1 are mapped as: (1) "Mature" soils of "acid rock" formed on granite, (2) "Skeletal Soils" where found on "calcareous rocks", and (3) "hard limestone" in sparse areas of "Soils formed under conditions of constant lime enrichment" according to soil maps of the Directorate of Overseas Surveys (1958). In reality, most of the soils on the hillslopes and terraces surrounding the surveyed sites were composed of an admixture of re-transported residuum of the "Skeletal Soils" and weathered granite (grus) that had moved downslope or by fluvial processes. Clearly, the calcareous chemistry of the limestone-derived soil makes big difference in vegetation composition, because the acid soils of the granite terrain support a low diversity of trees typified by pines, whereas soils where hillslopes are contributing calcareous materials support a much higher diversity of tree, shrub, and vine species.

<u>II.2.B.2. Area 2 Description (Vaca Plateau Uplands).</u>

Area 2 is situated on an upland summit well within the eastern side of the Vaca Plateau. There were no surface streams at this site. The upland has very gently sloping topography with little surface drainage. Soils appear very organically enriched and they are very high in clay content. Large desiccation cracks (1-2 cm wide) were visible in the surface of the soil during the field visit in June 2010. These desiccation cracks and the slippery nature of the clay soils indicates high content of expandable clay minerals, such as the smectite group. That is, the clay minerals expand and contract significantly upon wetting and drying, respectively. Soils in area 2 were mapped by Directorate of Overseas Surveys (1958) as "Soils formed

under conditions of constant lime enrichment," specifically as soils of a "tropical moist environment."

II.2.B.3. Stream Measurements by Site.

As detailed earlier, the Southern Cayo Site is situated from 16° 30′ N latitude to 17° 15′ N latitude and 88° 30′ W longitude to 89° 45′ W longitude. Interior to this general location, the study area was further divided into eight unique fluvial sites (F1-F8). The specific location (in Universal Transverse Mercator [UTM] projection) of each of the observed fluvial sites is found in Table 5.

Table 5. Fluvial Site Locations
UTM Zone 16 (WGS84)

Fluvial Site	Easting	Longitude	Northing	Latitude
F1	286323	89 0 24.7W	1878290	16 58 43.3N
F2	286282	89 0 26.1W	1878245	16 58 41.8N
F3	286077	89 0 33.0W	1878212	16 58 40.6N
F4	286043	89 0 34.1W	1878215	16 58 40.7N
F5	285981	89 0 36.2W	1878185	16 58 39.7N
F6	286347	89 0 23.5W	1877286	16 58 10.6N
F7	286341	89 0 23.7W	1877149	16 58 6.2N
F8	286380	89 0 22.4W	1877116	16 58 5.1N

Physical measurements of the fluvial systems at the eight study sites were made so as to accurately quantify the stream geomorphology. Various measurements of the stream characteristics are found in Table 6.

Table 6. Fluvial Characteristics (by site)

Stream Site	*Maximum Valley Relief (m)*	*Minimum Valley Relief (m)*	*Maximum Valley Width (m)*	*Minimum Valley Width (m)*	*DEM Channel Slope (m/m)*	*Local Slope (m/m)*	*Channel Width (m) Upstream*	*Channel Width (m) Downstream*	*Bed Material*	*Habitat*
F-1	480 (44)	436 (32)	309	77	0.12	0.11	10.1	5.4	Bedrock, Gravel	Run
F-2	477 (44)	433 (37)	339	68	0.12	0.13	6.84	11.05	Sand, Bedrock	Pool
F-3	479 (90)	389 (42(	664	116	0.12	0.03	5.6	4.35	Sand, Fine Gravel	Riffle to Pool
F-4	509 (114)	395 (86)	1141	79	0.12	0.2	5.1	6.35	Sand, Fine Gravel	Pool
F-5	480 (86)	394 (46)	720	90	0.07	0.16	4.3	7.15	Sand, Fine Gravel	Running Pool
F-6	484 (53)	431 (33)	532	60	0.21	0.11	0.8	1	Bedrock, TUFA	Rapid
F-7	483 (46)	437 (15)	295	65	0.06	0.07	2.48	4.3	Boulder, Cobble	Run
F-8	479 (41)	438 (10)	300	64	0.06	0.08	2.88	4.7	Boulder, Cobble	Boulder, Run

Site F-1 was the first site that was documented on the Rio Frio river system which is a major tributary and drains to the Macal River. This section of the reach had an active channel bed width of 5.4 m downstream and 10.1 m upstream along with a water width of 10.1m upstream and 1.35m downstream. The dominant bed material for this reach was bedrock and gravel and the physical habitat of this section was characterized by a run. The stream profile of this site is shown in Figure 15.

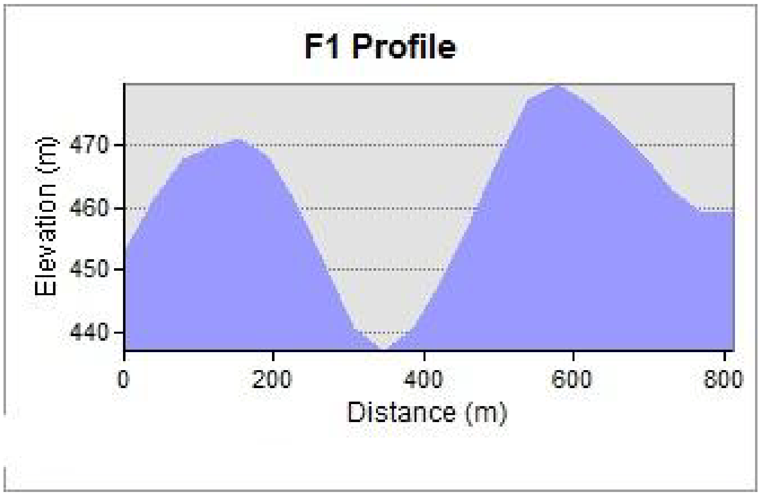

Figure 15. Stream Profile of F-1.

Site F-2 is located approximately thirty (30) meters downstream from F-1. The wetted water width upstream and downstream is 8.06 meters. The active channel bed width upstream is 6.84 m and downstream is 11.05 m. The reach for F-2 has a dominant bed material of sand and bedrock with the physical habitat of the cross-section consisting of a pool. The stream profile of this site is shown in Figure 16.

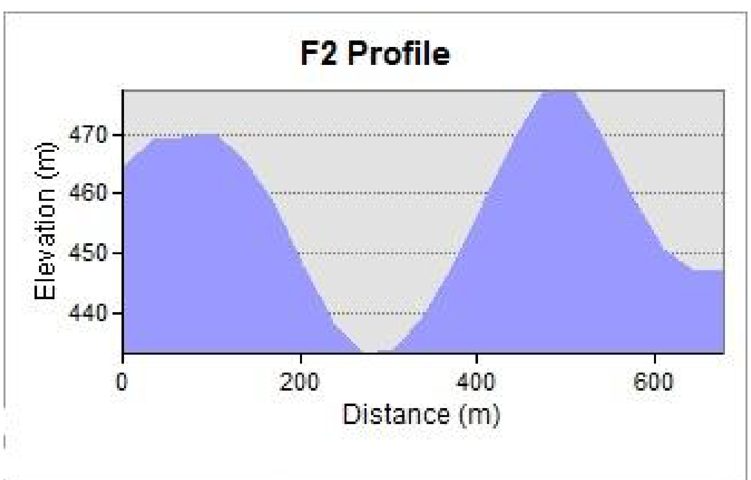

Figure 16. Stream Profile of F-2.

Site F-3 is a reach also along the Rio Frio. This section of the stream is located below a set of falls in a riffle. The upstream channel bed width is 5.6 m and the downstream channel bed width is 4.35 m. The wetted width of F-3 upstream is 5.47 m and the downstream wetted width is 4.31m. The channel bed material on this section of the reach is predominantly sand and fine gravel with a scattering of cobble and boulders. The habitat is characterized as a riffle grading down into a pool. The stream profile of this site is shown in Figure 17.

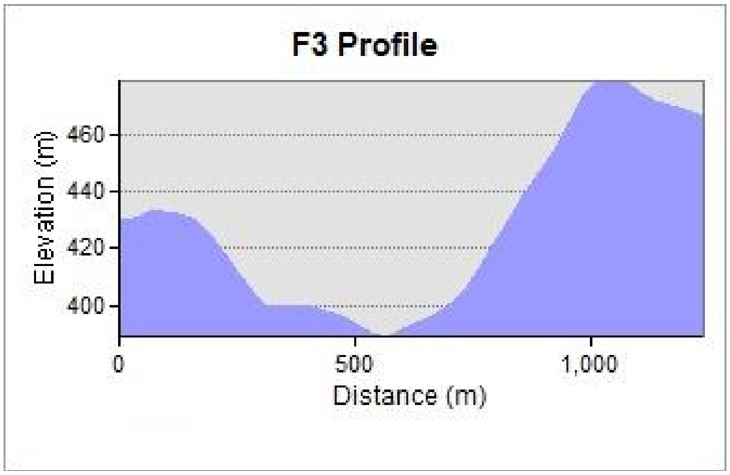

Figure 17. Stream Profile of F-3.

Site F-4 has an upstream active channel bed width of 5.10 m and a downstream active channel bed width of 6.35 m. The wetted water width of the upstream section is 5.05 m and the downstream wetted water width is 3.73 m. The channel bed material is sand and fine gravel with a habitat characteristic of a pool. The stream profile of this site is shown in Figure 18.

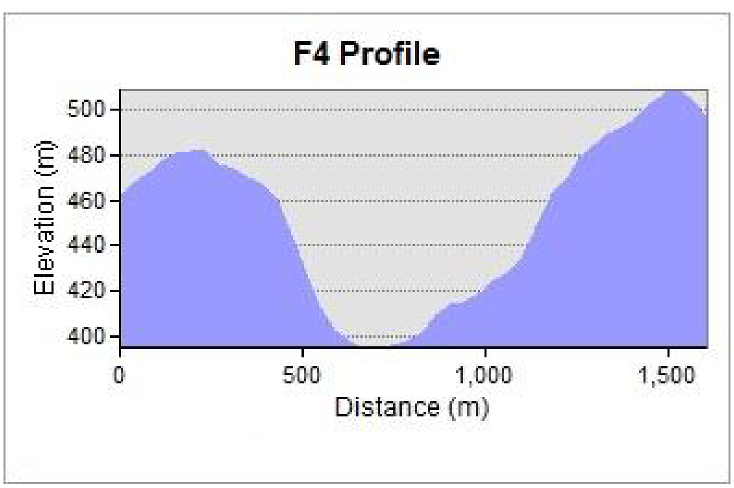

Figure 18. Stream Profile of F-4.

Site F-5 is a channel bed site with material predominantly composed of sand and fine gravel with a habitat cross-section of a running pool on a bend. The upstream active channel bed width is 4.30 m and the downstream channel bed width is 7.15 m. The water width in the upstream is 2.94 m and the downstream water width is 7.14 m. The stream profile of this site is shown in Figure 19.

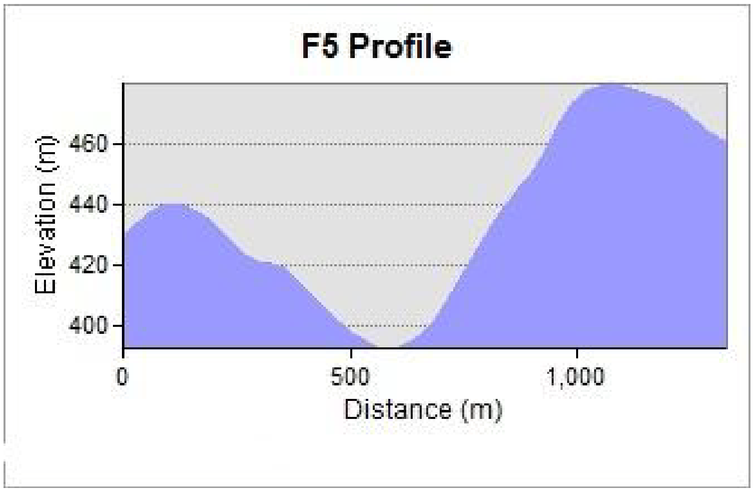

Figure 19. Stream Profile of F-5.

Site F-6 is a fluvial site with bed material consisted of bedrock, tufa and boulders. The tufa consists of the right bank and provides a concrete like bank protection that is not easily erodible. The channel habitat is bedrock rapids and pools. The upstream active channel width is 0.80 m while the downstream active channel bed width is 1.00 m. The wetted width in the upstream direction is 0.53 m and downstream water width is 1.00 m. The stream profile of this site is shown in Figure 20.

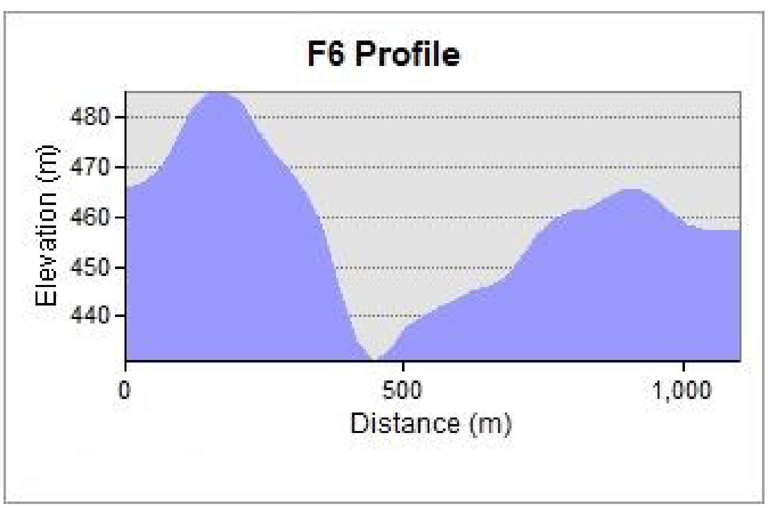

Figure 20. Stream Profile of F-6.

Site F-7 is a fluvial site characterized as an alluvial reach that lies between steep bedrock sections of the tributary of Area 2 within the Rio Frio drainage basin. The upstream channel bed with is 2.48 m and the downstream active channel bed width is 4.30 m. The wetted width in the upstream reach is 2.57 m and the wetted width downstream at fluvial site seven (7) is 4.15 m. The bed material consists of boulder, gravel and cobble while the physical habitat of the cross-section is a run. The stream profile of this site is shown in Figure 21.

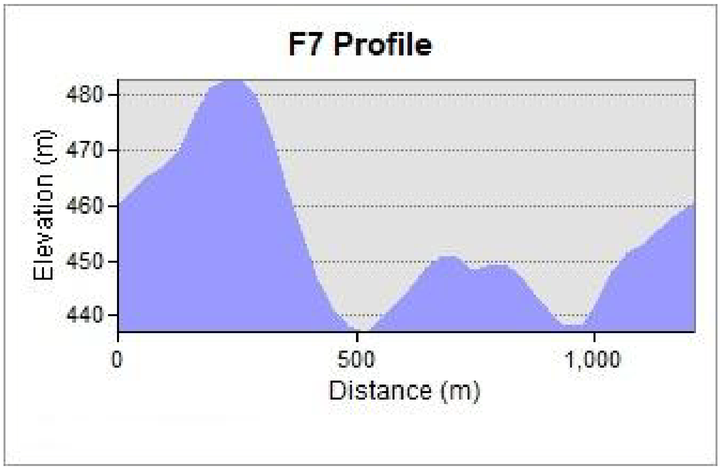

Figure 21. Stream Profile of F-7.

Site F-8 is a fluvial site characterized by a tufa that dominates the entire left bank which, as stated above, adds additional protection from fluvial erosion. The habitat of F-8 is a boulder run with a bed material of boulder, cobble and gravel. The upstream and downstream channel bed width and water width is similar to that of Site F-7. The stream profile of this site is shown in Figure 22.

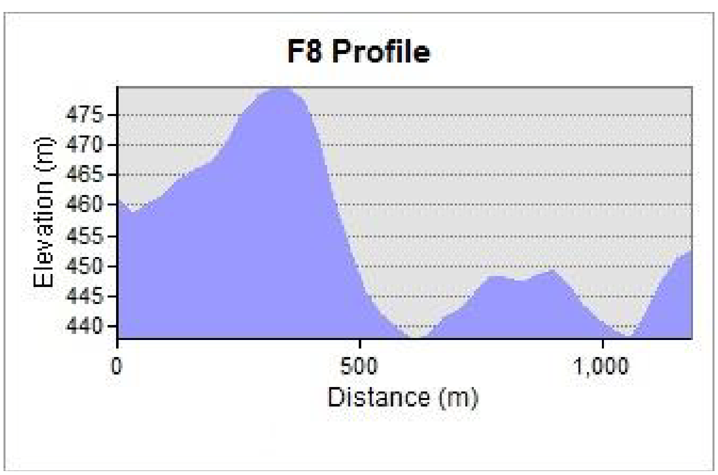

Figure 22. Stream Profile of F-8.

CHAPTER III

EVALUATION OF TESTING CAPACITY

In addition to the ongoing testing requirements described above, a vision for future requirements includes the need to test new technologies being developed for the Objective Force and the Future Combat System. This testing would include: sensors (airborne/space-borne/terrestrial and man-portable systems); information, data networking, and communication technologies based on electromagnetic transfer; cloaking, and reduced signature technologies; and product improvements of existing systems (as a cost-saving measure to replacement systems). Further descriptions of these testing methods and possibilities follow in the paragraphs below.

The use of hyperspectral image data has been successfully employed worldwide in ongoing counter drug operations. With all objects reflecting, absorbing, or emitting electromagnetic radiation based on their composition, hyperspectral sensors using reflected solar radiation (0.4 micrometers - 2.5 micrometers wavelength range), capture unique spectra, or the 'spectral signature' of an object. Using a procedure called BandMax™, spectral characteristics of targets are compared to background signatures. This enables significant spectral features indicative of spectral target material to be exploited, whereby atmospheric effects are avoided and ultimately "false alarms" from similar objects are reduced. This approach provides a 'yes/no' answer to the question of whether or not an object is present, with a statistically high degree of confidence (SORC, 2005). Plastics and some other unique materials required in running drug labs do not naturally occur in the natural landscapes of the tropics and are, therefore, frequently selected as target material (see Figure 23). Demonstrating this differentiation technique, the spectral radiance of a chemical pit is compared with that of drying coca plants in Figure 24. In addition to these sensor techniques, new information and communication systems, such as Land Warrior, spearheaded by PM Soldier, will provide the individual Soldiers with advanced technologies and weapons for the battlefield of the 21st century. There will be an increased focus on dual-use or multi-use technologies that have high payback, such as environmental technologies for unexploded ordnance detection/location and similar applications. All of these technologies are highly sophisticated and complex. As such, test and evaluation of such new technology and related methods will require a thorough understanding of the environmental factors affecting their technical performance, as well as the synergistic environmental effects that challenge equipment operability and reliability.

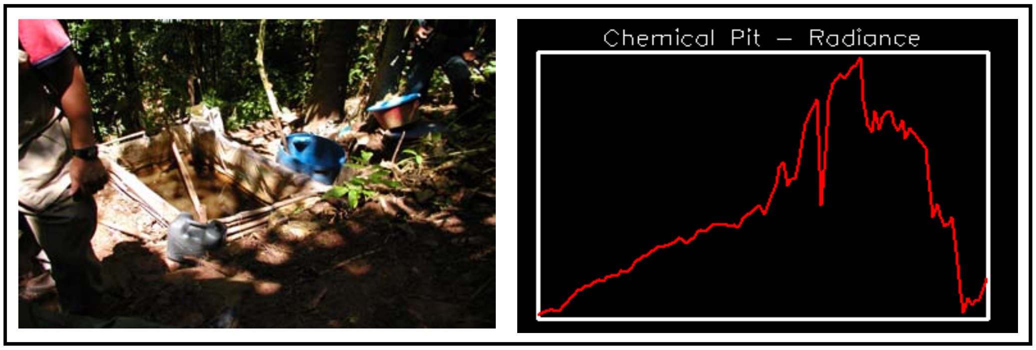

Figure 23: Chemical pits return a unique spectra to a hyperspectral sensor (Galileo Group, 2005).

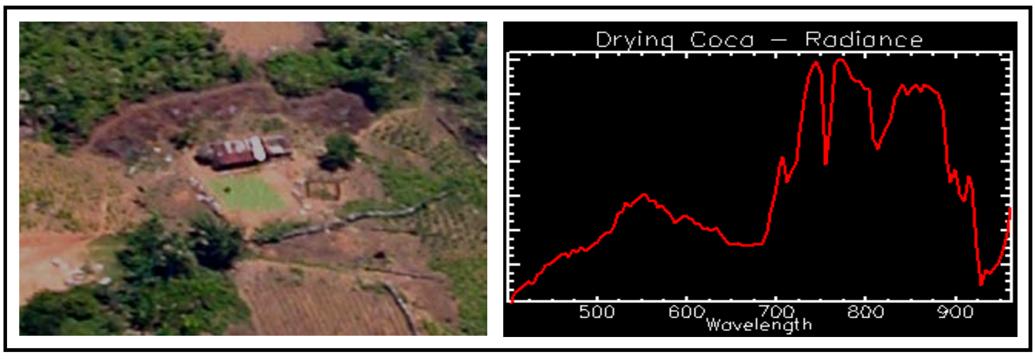

Figure 24: Spectra for drying cocoa leaves gathered by airborne hyperspectral remote sensing (Galileo Group 2005).

Tropical test centers allow evaluation of a variety of remote sensing modalities. Midwave (3-5 micron wavelength) and longwave (8-16 micron wavelength) infrared technologies rely upon the thermal temperature difference between background and target for detection. Small diurnal and annual temperature ranges reduce the opportunity for strong target-background temperature differences in tropical environments unless the target itself is a source of energy that provides a detectable thermal temperature contrast. In addition, infrared transmission through the atmosphere is attenuated by clouds, fog, and water vapor, which tests the sensitivity of infrared systems.

Light detection and ranging (LIDAR) operates by sending laser transmissions in the visible to near infrared through the atmosphere to a target, and uses the time delay between the transmitted signal and the reflected signal return to measure the distance to objects. It is useful, for example, for mapping the shape of targets beneath forest canopies. Cloud cover, precipitation, and water vapor attenuate LIDAR signals making tropical environments appropriate for testing this technology. In addition, the multi-layer canopies in many tropical ecosystems

challenges the capability of LIDAR signals to penetrate to targets. It is believed that "ground truthing" of the terrain (study site) using a terrestrial LIDAR collection system would benefit any further testing done by experimental airborne or spaceborne LIDAR and/or RADAR sensing systems

As with LIDAR, multispectral and hyperspectral technologies rely upon transmission through the atmosphere in the visible and infrared wavelengths. Since multispectral and hyperspectral technologies are passive, receiving reflected light from surfaces, they are defeated by the frequent cloud cover and fog of tropical environments. In addition, water vapor, oxygen and other gases differentially attenuate and change the reflected energy spectrum affecting the ability to accurately characterize targets.

Passive millimeter wave (MMW) systems, utilizing microwave radiometers, rely upon the brightness temperature of objects at the operating frequency for detection capability. MMW, especially for frequencies greater than 20 GHz, are attenuated by water vapor, cloud drops and precipitation. The high water vapor content of tropical atmospheres, typically greater than 30 mb partial pressure, and frequent cloud cover, fog, and precipitation with large drops, attenuate MMW signals making it a challenging environment for testing.

Radar crosses a broad frequency spectrum, from megahertz through terahertz. As frequency increases, wavelength decreases, and wet surfaces and liquid water drops attenuate and scatter transmitted and backscattered signals. Heavy foliage cover provides opportune camouflage for targets. As result, multi-canopy tropical environments with thick, water-filled leaves provide an opportunity to evaluate the ability of radar to penetrate foliage to detect targets beneath canopies. Dense foliage also provides an opportunity to test polarization techniques and longwave radar technologies, such as FOliage PENetrating radar (FOPEN) operating in the MHz range, for detecting and identifying targets beneath the canopy. High frequencies of fog, cloud and heavy rainfall can attenuate higher MMW radar frequencies, and the permittivity of wet soils may limit the capability of ground penetrating radar.

Acoustic sensing is affected by atmospheric and terrain related features, including vegetation. The structure of tropical forests may duct acoustic signals, and the closed forest canopy of wet leaves may absorb the acoustic signal. However, warm, convective weather conditions may also maintain a turbulent boundary layer which limits acoustic ducting.

Seismic signals are scattered, reflected, and attenuated by depth to bedrock, bedrock structure, soil density, and water table depth. The deeply weathered iron and aluminum rich soils of tropical environments often places bedrock at large depths and may render bedrock depth an insignificant factor in seismic signal

propagation. However, the potential for high water tables may impact upon the strength and directionality of seismic signals.

The capacity for testing at this study site is substantial. Many of the new technologies being considered for the Objective Force and the Future Combat System would be challenged here. This testing should include multiple sensors; information, data networking, and communication technologies based on electromagnetic transfer; cloaking, and reduced signature technologies; and product improvements of existing systems.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

IV.1. Conclusions.

Southern Cayo was successfully characterized as to its capacity to support environmental testing of military equipment and systems. Specifically, as part of the study, the research team collected data from various locations with representative foliage for the development of a mathematical model(s) and/or or technical description(s). Locations both away from and near stream and/or river systems were considered. Effects of various environments on ground and airborne sensor systems were evaluated. This site proves to be a good to excellent choice for a variety of test missions. The strength of Southern Cayo is diverse canopy, its isolation from cultural activities that could interfere with some types of tests, and its challenging terrain, which is a combination of steep slopes and surface cover. This is an excellent site for a variety of sensor and remote sensing technology tests, although the absence of level forest terrain may be delimiting for some tests. Administratively, the site is easily accessible from the United States and political environment currently appears to support testing of military equipment.

Overall, this site is among the best sites for tropical testing examined to date, based on good environmental conditions and excellent access to be able to conduct all types of tests. The two general categories of testing not supported by this site are tracked vehicle mobility and large caliber weapons testing. The site is not large enough to support the tracked vehicle testing, while land use restrictions would likely not allow for weapons or ammunition testing. Further, the level of damage that is produced in tracked vehicle testing would most likely not be acceptable to our hosts in that it may interfere with their uses of the land. It is possible that a small driver training course for their security foreces could double as a small vehicle test track, but that would be a matter for further discussion.

IV.2. Recommendations.

- The Southern Cayo site should be incorporated into the suite of sites available for tropical testing. This site offers unique features that would add to USSOUTHCOM's overall ability to test in the tropics.
- The site could become a primary site for developmental testing of sensor and communications systems. The vegetation, slopes, and rocky surface create a perfect location to challenge both surface and airborne sensor systems.
- The site could be developed for human factors testing, which would require installing man-pack courses within the area. This would provide a variety of

trafficability and land navigation conditions that could be valuable over the range of tests that could be supported.

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APPENDIX 1

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APPENDIX 2

PHOTOGRAPHS OF VEGETATION SITES

Figure A2-1. Photos from V-1
(a= facing north, b=facing south, d=facing west, d=facing east, e=facing upward)

Figure A2-2. Photos from V-2
(a= facing north, b=facing south, d=facing west, d=facing east, e=facing upward)

Figure A2-3. Photos from V-3
(a= facing north, b=facing south, d=facing west, d=facing east, e=facing upward)


a


b


c


d


e

Figure A2-4. Photos from V-4

(a= facing north, b=facing south, d=facing west, d=facing east, e=facing upward)

Figure A2-5. Photos from V-5
(a= facing north, b=facing south, d=facing west, d=facing east, e=facing upward)

Figure A2-6. Photos from V-6
(a= facing north, b=facing south, d=facing west, d=facing east, e=facing upward)

Figure A2-7. Aerial image of fluvial study site area.

Figure A2-8. Aerial image of Macal River.

Figure A2-9. Aerial image of vegetation study site area (V1-V4). Click HERE to find a video of Vegetation Study Sites V1-V5 and the Fluvial Study Sites.

Figure A2-10. Aerial image vegetation study site area (V6). Click HERE to find a video of Vegetation Study Site V6.

Figure A2-11. Old road in study area.

Figure A2-12. Old foot trail in study area.

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APPENDIX 3

METHODOLOGIES USED IN CHARACTERIZATION OF TEST SITE

A3.1. Vegetation Measurement Methodology

Augmenting the subjective description of vegetation, objective measurements of canopy density were made using the LAI-2000 Plant Canopy Analyzer (Figure A3.1). This device employs an innovative technique for making rapid, nondestructive measurements of leaf area index (LAI) and other plant canopy structure attributes such as Mean Tip Angle (MTA). Rapid sampling means results in cost savings which can be substantial when compared to direct measurements made with other instruments (such as an area meter). Measurements can be made under a variety of sky conditions, and in canopies ranging in size from short grasses to forests. The LAI-2000 calculates LAI and other attributes from radiation measurements made with a "fish-eye" optical sensor (148° field-of-view). Measurements made above and below the canopy are used to determine canopy light interception at 5 angles, from which LAI is computed using a model of radiative transfer in vegetative canopies. Measurements are made by positioning the optical sensor and pressing a button; data are automatically logged into the control unit for storage and LAI calculations. Multiple below-canopy readings and the fish-eye field-of-view assure that LAI calculations are based on a large sample of the foliage canopy. After collecting above-canopy (or clear-canopy) and below-canopy measurements, the control unit performs all calculations and the results are available for immediate on-site inspection. Diffuse non-interceptance (variable **DIFN**) is the fraction of sky visible from below the canopy.

Figure A3-1: LAI-2000.

A3.2. 360° Terrestrial Imaging Methodology.

Capturing effective imagery of study sites in tropical areas has been a consistent challenge for researchers. Immersive imagery (360° view) is now possible. Figure A3-2 graphically shows the differences between a standard view image collect, megapixel view image collect and the immersive view iPIX image collect.

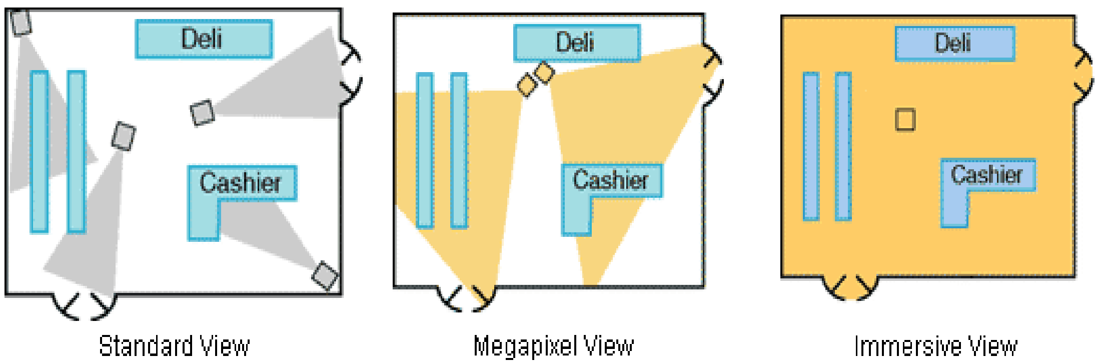

Figure A3-2: Image collection examples from different views.

The iPIX imaging system (Figure A3-3) was used in the project for this purpose, where the images collected with the system provided interactive visual references of the potential test locations. A Nikon CoolPIX P6000 handheld camera was used to collect the imagery. The camera was equipped with a specialized fisheye lens which captured a 185° field of view (FOV) at the focal point. In addition, a custom-designed, tripod-mounted bracket held the camera in place which enabled two pictures to be taken from opposite directions ("locking points" in the bracket held the camera fixed in place during imaging). The result from this image collection method was two 185° FOV photos from the same focal point, pointed in the exact opposite direction of each other. Before collection of imagery, the camera was adjusted to account for the fisheye lens attachment as well as the variability in lighting due to rotation of the camera during collection of image pairs. First, a GPS data point was collected with a Garmin GPS receiver (Figure A3-4). Next, the camera was mounted on the tripod with a specialized mount. An orientation marker was then placed on the ground (facing north) in order to provide a directional reference within the imagery when creating the final executable file. The lighting was controlled manually and was adjusted before every photo was taken in order to maintain image sharpness in the seam areas. Employing a 2-second timed shutter option on the camera (which eliminates instability caused by manually depressing the shutter button and allows the photographer to walk outside of the viewable area), the first image was collected. The camera was then rotated 180° on the swivel mount, the lighting was adjusted, and the second image was taken. This process was repeated two additional times to ensure a quality stitch during post processing.

Figure A3-3. iPIX Imaging System.

Figure A3-4. *Garmin Rino 530CSx.*

The result was six corresponding images for each collection point (triple redundancy). Figures A3-5 and A3-6 display two examples of the raw data gathered with the iPIX system in one location. The images were taken from the same tripod location, with the camera lens position offset 180° by the specialized camera mount.

Figures A3-5 and A3-6. iPIX image pair collected in Belize, taken while “pointing” the camera in opposite directions.

The two photos were then stitched together using specialized software, producing a 360° interactive iPIX product. A user is able to explore the entire area where the pictures were taken from, as if he or she were standing where the tripod was placed. The result is a comprehensive all-around view from where the iPIX system was located. The end-state purpose of collecting the iPIX imagery is to provide customers with a visual representation of the various test sites employed by tropical settings.

A3.3. Stream Measurement Methodology

Not all stream measurement techniques are uniform. For the purpose of this report, a naming convention was established to differentiate between the vegetation and fluvial analysis within sites. The letter **V** was used for vegetation and **F** was designated for fluvial sites. This protocol remains consistent throughout the remainder of this report. The maximum valley relief at each **F** site was measured through the careful use of Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) Global Digital Elevation Map (GDEM) data. By generating stream profiles from the GDEM and utilizing ESRI's ArcMAP function in ArcGIS, maximum valley relief for each surveyed site was determined. This value results from taking the highest elevation value on the summit and subtracting it from the lowest elevation value in the stream on a line of section perpendicular to the stream valley. Similarly, the ASTER data were used to generate the other measures of valley morphology indicated below. The minimum valley relief is determined by subtracting the stream elevation from the summit elevation of the lowest of the ridges on either side of the valley. The value for maximum valley width is determined by measuring the width of the valley perpendicular to the stream site at the height of the lowest summit on either side of the valley. The minimum valley width is determined as the width of the alluvial valley floor. The DEM channel slope was calculated through the analysis of the ASTER GDEM imagery of the Mountain Pine Ridge district in the country of Belize. This involved measuring the "rise-over-run" at each of the eight (8) fluvial areas documented as a result of subtracting the downstream value from the upstream value (rise) and dividing that by the linear distance. The local slope was verified through the use of the photographic documentation captured from the IPIX camera system. Through the use of 1 x meter scale bars incorporated in the photographs, each of the eight (8) fluvial sections secured photographically, achieved a computation of the local slope by deducing the downstream value of the top of the thalweg from the upstream value over a known distance. Finally, the channel width upstream and downstream was also determined through the investigation of IPIX photographic documentation of the eight (8) fluvial sites monitored for this study. Utilizing the horizontal and vertical 1 x meter scale bars allowed for precise measurement of the upstream and downstream channel width on all of the sites photographed.

APPENDIX 4

INTERACTIVE MAPS AND IMAGES

The image maps and map that follow on the next four pages facilitate quick access to the GRID files as well as a JOG GeoPDF of the study area. The image maps have hot links to the GRID files. The stitched iPIX images are available digitally (assuming you have a digital version of this document. Your version of Adobe Acrobat Reader must have the TERRAGO Toolbar loaded. The link found HERE facilitates this requirement. NOTE: You must have Adobe Reader 8.0 or later already loaded on your computer. If the iPIX Viewing software was downloaded (also HERE), the iPIX images can be viewed from directory link HERE.

APPENDIX 5

THE TESTING MISSION

A5.1. Overview of the Testing Process.

The testing and evaluation of equipment and systems in the natural environment is conducted using accepted scientific protocols and established engineering practices. This assures repeatability, experimental control, and validity of test results. Many aspects of the testing process are conducted over long periods of time and, therefore, a fundamental requirement for a test location is the constant presence of tropical conditions that provide the requisite challenges to the item undergoing testing. Testing also requires a well-characterized and understood suite of tropical field sites that provide environments that are fully representative of those in which Soldiers, systems, and materiel may be fielded during combat.

The test and evaluation of equipment and systems is a complex continuum that begins with basic proof of concept, then develops an understanding of how environmental effects impact equipment throughout its life cycle, and finally tests systems with operators. The test continuum is a participative, iterative process among developers, test personnel, and Soldiers, during the RDT&E process in multiple test phases. Each phase focuses on maturing the item and furthering it along for inclusion in the DoD inventory. Any number of very specific test facilities and capabilities are required to meet various needs during the course of the overall testing process. Natural environment developmental testing addresses technical issues and criteria that require realistic, calibrated test sites and courses where repeatability and control can be ensured over time and events. Operational Testing addresses force-on-force system effectiveness issues. Both types of testing require representative, natural environments. These facilities and capabilities are summarized in the following section.

The wet tropical environment is the most diverse and complex natural environment in the world and, consequently, is one of the most challenging for units, individuals, equipment, and systems. Modern sophisticated technology, with complex integrated electronic circuitry, is more critically affected by tropical factors than the simpler electromechanical systems of the past. The effects of heat, humidity, direct insolation, and biological degradation by organisms such as bacteria and fungus, coupled with a dense cover of a multi-canopy jungle, not only attack and deteriorate equipment, but also create a most hostile natural environment in which the individual must successfully wield the technology to accomplish their military mission.

A5.2. Types of Testing.

Current environmental testing by the DoD can be divided into five broad categories: (i) equipment and system development testing [30% workload]; (ii) equipment and system operational and human performance testing [50%]; (iii) munitions testing including long term storage [15%]; (iv) specialized testing [3%]; and (v) vehicle mobility testing [2%]. This testing is encompassed and described by a matrix of six test categories or groups that have common environmental test requirements as described below.

A5.2.A. Developmental Testing.

Developmental testing typically encompasses the prototype testing of new equipment. It focuses on all types of equipment, systems and materials with current emphasis on communications systems and electronics, ground and air sensor systems, and chemical-biological detection systems. Exposure and wear testing of equipment under both open and jungle conditions is an integral component of this activity. Sites for tropic developmental testing should have "robust" environmental characteristics that provide climatic conditions close to those described in AR 70-38, so as to provide the maximum tropical environmental challenge to the performance envelope of these items. These include (i) a dense jungle canopy for obscuring ground-placed targets to airborne sensors, (ii) a well-developed soil profile, (iii) a dense vegetative understory, (iv) topography for challenging line-of-sight communication, and (v) a hot humid jungle environment with abundant biologic decomposition to produce the volatile compounds that challenge chemical-biological detection equipment. An intense tropical environment includes a diverse suite of biological degraders consisting of bacteria, fungus, and insects to challenge long-term material integrity.

A5.2.B. Human Factors (HF) Performance Testing.

This testing is directed toward the operation of equipment and systems in the manner employed during use by the DoD. It allows for testing of both the functionality of the equipment, as well as for the performance of the individual. High temperature and humidity stress the service members, thus lessening the ability to move quickly, work long hours, and successfully manipulate complex equipment and systems. The tropical environmental characteristics required are high humidity, high temperature, a well-developed understory and canopy, and appropriate geomorphic features such as relief, streams, and soils. In actual combat conditions, all of these factors combine to create a dark and foreboding atmosphere that can affect individuals' attitudes and sense of well-being, and thus their ability to accomplish their mission. It should be noted that, scientifically, the characteristics of an ideal site for human factors testing requires the most complete set of

environmental factors; in fact, all 14 characterizing parameters are useful in human factors testing. This can also be said for an ideal tropical training site except that the space requirements for training are much larger than what is needed for human factors testing.

A5.2.C. Long-Term Exposure and Testing of Munitions.

This activity is focused on the long-term exposure of munitions and testing of small (≤40 mm) and large (>40 mm) weapon systems in tropical environments, in both open and jungle settings. Munitions of all types, particularly larger caliber, are stored for protracted periods to evaluate their stability when subjected to tropical conditions. The testing of munitions generates military unique test requirements and, as such, the military infrastructure requirements of established ranges and approved storage areas for munitions must overlay, or be in close proximity to, the environmental test areas. Small caliber munitions involved in operational testing require a similar military-unique infrastructure, as well as the usual environmental characteristics of high heat and humidity identified in AR 70-38. Large caliber weapon systems must be subjected to both exposure and operational testing within the tropical environment. Ultimately, all munitions firing must be conducted on ranges approved for all safety standards. Testing of smokes and obscurants requires a relatively flat area in areas of restricted access.

A5.2.D. Vehicle Mobility Testing.

This testing is directed toward evaluating mobility performance of wheeled, tracked, and towed vehicles. It includes the testing of trucks, tanks, towed weapons, trailers, and any other types of vehicular system that must move on wheels or tracks. The environmental requirements include a variety of tropical soils capable of yielding mud, slopes up to 60%, varied vegetation in stem size and density, and surface water features that are representative of conditions found in tropical settings worldwide. Continued long-term access to the same mobility courses is a requirement, so that comparative analysis over the same set of slopes, soils, terrain, and environmental conditions can be utilized as new test requirements emerge.

A5.2.E. Operational Testing.

Operational Testing is the final end testing of an item or system before it enters into the DoD inventory. Typically, the system is provided to the individuals who are conducting normal field exercises, force on force activities, or field support activities, depending on the item and its projected use. Realistic scenarios are required including the battlefield environment and associated maneuver facilities. Movement is relatively unconstrained at this point and the geographic constraints associated with Developmental Testing sites are no longer applied. It is not

uncommon that elements of Developmental Testing will be embedded within or combined into Operational Testing, a trend likely to continue in the future.

APPENDIX 6

BACKGROUND OF TROPICAL TESTING RESEARCH

A6.1. Introduction.

The history of conflict has documented the challenges for armies attempting to conduct military operations in the heat, humidity, and dense biologic setting that characterize the tropical environment. The U.S. experience in World War II in the Pacific Islands and in Southeast Asia during the Vietnam War clearly demonstrated the hazards to men and equipment posed by these extreme environments. From this history two clear lessons emerge: (1) Equipment must be tested to assure it can stand up to and perform under these demanding conditions; and (2) units must train in the harshest tropical settings to be prepared to accomplish full spectrum operations within this domain.

Roughly 15 percent of the earth's land mass is classified as tropical primarily using parameters of climate and land cover. Yet, since 1960, some 75% of all international and internal conflicts have been in countries whose borders are totally or partially within the wet tropical environment. Researchers examining past conflicts to better understand the security threats of the future have reached the conclusion that the countries lying within the tropics are the most likely locations for future conflicts (e.g., Lee, 1999; Barnett, 2004). Further, studies examining the sources of insecurity posed by global environmental degradation regard the tropical regions of Africa, Asia, and the Americas as the most likely locations of instability in the future (King, 2000). Recent operations in Somalia, Rwanda, Haiti, Panama, East Timor, and elsewhere have only reinforced the need to be prepared for tropical conditions. Clearly, by any metric one can use, the DoD must be prepared to deploy and operate successfully in the tropical environment.

A6.2. Environmental Testing.

The US DOD and several of its military allies have a long history of operating testing and/or training facilities in the hot, humid tropics (e.g., the United Kingdom in Belize, France in French Guiana, and Australia in its state of Queensland). Guided by requirements in numerous performance standards (MIL STDs), environmental conditions and their effects are to be given realistic consideration in the research, development, test, and evaluation (RDT&E) process for materiel used in combat by the DoD. As a result, testing and evaluation in the tropical environment of material, equipment, and systems, as well as human performance, is well established. In example, the mission of testing in extreme natural environments for the Army (US Army, 1979b) resides with the Army Test and Evaluation Command (ATEC) and is vested with Yuma Proving Ground (YPG). Presently, this

mission is accomplished at desert, arctic, and sub-tropical test facilities in the United States (arctic at Fort Greeley, AK (CRTC); desert at Yuma Proving Ground, AZ (YTC); and sub-tropic at Schofield Barracks, HI (TRTC). Temperate environment testing is the responsibility of the Aberdeen Test Center (Aberdeen Proving Ground, MD).

A6.3. Selecting Study Sites - Background.

Testing of materiel, equipment and systems, together with human performance evaluation under tropical conditions took place in the Canal Zone area of the Republic of Panama as far back as WWI. This mission evolved into the Tropic Test Center (TTC) in 1962, which supported specific Army test functions in response to evolving military needs through the 1990s. In parallel, the Army's Jungle Operations Training Center (JOTC) was operated at Fort Sherman in Panama, conducting individual soldier and collective unit training for the Army and land forces from all services within the DoD. The tremendous value of the JOTC experience to prepare units for missions in the tropics and to develop troop leading skills was well respected throughout the Army. However, under the terms of the Carter-Torrijos Treaty of 1977, the U.S. military mission in Panama was required to relocate from the country by December 31, 1999.

In 1998, at the request of Yuma Proving Ground (YPG), the Army Research Laboratory's Army Research Office (ARO) convened an expert panel to undertake a study to identify areas across the globe that could replace the test environment that was being lost as a result of the Army's departure from Panama. The initial product of the study panel, ***A Technical Analysis to Identify Ideal Geographic Locations for Tropical Testing of Army Materiel and Systems*** (King et al., 1998) examined the DoD (Army) tropical test mission to define the conditions that best provide the environmental challenges needed for tropical testing, in the 21st century. The 1998 study defined the climatic, physical, and biological characteristics of the "ideal tropical test environment" and identified regions of the world that best provided the combined parameters for such an ideal location. Worldwide, 16 areas were identified in the 1998 study (King et al., 1998; 2004) as suitable localities for DoD tropical testing (Figure A5-1). The first group of six geographic areas, ordered in terms of their relative proximity to the continental US, included: northern Honduras, the Isthmus of Panama, French Guiana/coastal northeastern Brazil (adjacent to Suriname), the southwestern New Guinea lowlands, low-moderate altitude areas of the East Indies in east-central Java and southeastern Borneo, and the Isthmus of Kra in Malaysia. The premier localities in this group for tropical testing were the Isthmus of Panama and the Isthmus of Kra because both areas offer a spectrum of tropical conditions and environments within a compact geographic area. A second group of 10 locations was identified that exhibited the general physiographic and biotic character, but failed to provide one or more of the other important elements

considered requisite of the ideal tropical environment for DoD testing. This group consisted of coastal Belize, Puerto Rico, southeastern Costa Rica, northwestern Colombia, portions of the Hawai'ian Islands and the Fiji Islands, the Philippines, New Britain-New Ireland, the coastal region of northern Queensland in Australia, and the Bangkok area of coastal Thailand.

The second phase of this project followed the recommendations from the initial study where it was concluded that no ideal tropical test location existed in the U.S. or in U.S. controlled properties, therefore, a suite of sites should be developed to better support a broad range of environmental requirements for tropical testing and training. The primary product of the second tropics panel was a geographic characterization model which has been used to compare candidate sites to the ideal conditions for tropical testing. It further allowed examining candidate sites with the critical and important environmental criteria applicable for each type of test to be conducted. From that point, the panel has conducted analysis on 6 separate geographic regions and evaluated and 24 specific sites within these 6 regions. The results of these site studies are published in the reports listed in Table A6-1.

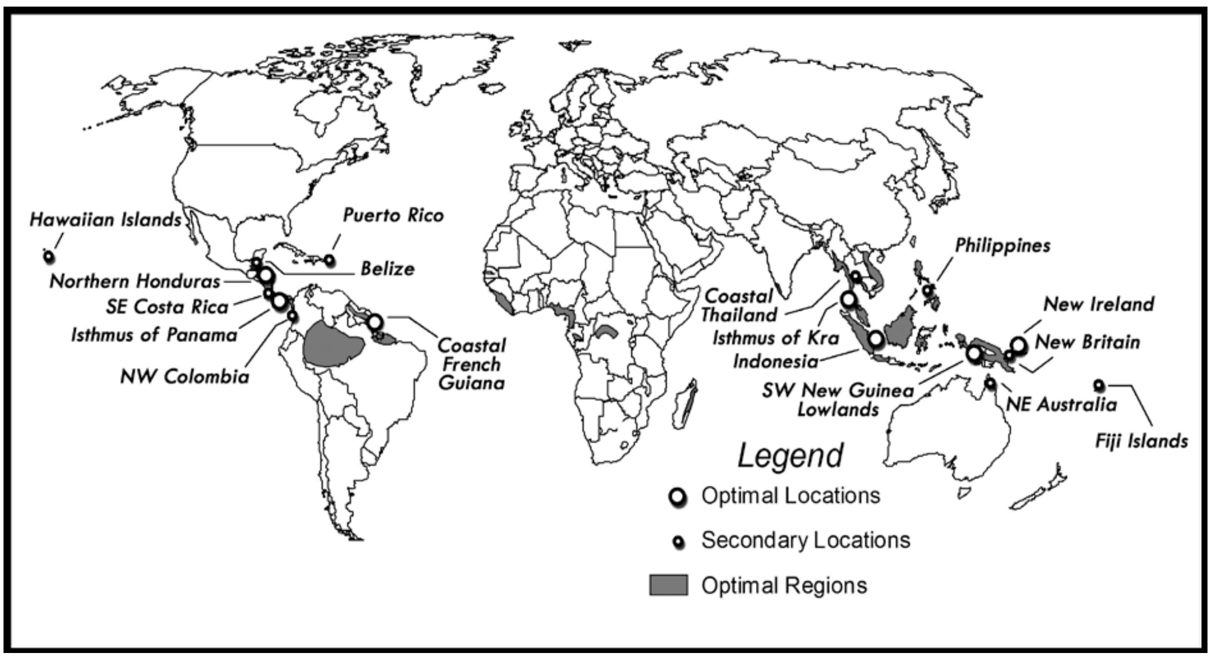

Figure A6-1: Optimal locations for developmental and operational tropical testing of military equipment, vehicles, and weapon systems (from King et al., 1998; 2004).

As of 2009, DoD is actively engaged in tropical testing; now employing a suite of sites that has evolved from the results and recommendations of previous panel work. Sites include locations in Hawai'i and capability for selected test missions in Panama, Honduras, and Suriname.

A6.4. The Ideal Tropical Test Site.

The requisite characteristics of the ideal environment for a tropical test facility are derived from complex interrelationships among the key factors of climate, terrain, and vegetation. Climate is the defining characteristic of a tropical region, whereas physiographic and geologic factors are closely associated, and the biologic manifestations (land cover/vegetation type) are a direct function of the combination of climate, physiography, and geology within a given region. The criteria identified as defining the ideal tropical test environment from a scientific basis (King et al., 1998) are summarized in Table A6-1.

A6.4.A. Climate Requirements.

Climatic criteria for the humid tropics are defined in Army Regulation, AR 70-38 (US Army, 1979a), which broadly classifies world climates into four "basic climatic design types." Each of these design types is characterized by one or more daily weather cycles. Two daily cycles in the 'basic climatic type' represent the humid tropics.

The ideal setting for a tropical test facility would lie in a hot and humid tropical climate regime to provide extremes of high relative humidity (RH) in a very high rainfall and near-constant high temperature environment. As such, the area encompassing the site should have annual precipitation in excess of 2,000 mm, monthly-averaged minimum temperature and RH in excess of 18-20°C and 60%, respectively, and mean monthly temperatures and RH of at least 25°C and 75%, respectively. Average rainfall would not fall below 100 mm in any single month, nor exceed 6,000 mm per year. These precipitation requirements address a desire for minimal seasonal variability and no impact on vegetation growth patterns (i.e., a preference for no absolute dry season). Regions experiencing tropical cyclone (hurricane or typhoon) activity should be avoided, unless all other physical factors indicate the site to be an optimal location. Ideally, a relatively compact area would exhibit variable conditions of climate (e.g., frequency/distribution of precipitation and temperature) across the spatial domain encompassing a landscape varying from coastal lowlands to steep mountainous relief.

A6.4.B. Physical Setting Considerations.

The requirements defined in the ideal test environment are best met by an area of sufficient size to contain the test mission, possessing significant variations in slope and relief across the site, with surface streams sufficiently large to support a variety of tests, surrounding land use that is compatible with the testing mission, and the absence of cultural/historical resources or conservation pressures that could infringe on testing. The area should not be a high-risk zone in terms of frequency of

natural hazards (e.g. tropical storms, volcanic activity, earthquakes, landslides, flooding, etc.). Also, it should not be affected by significant adverse anthropogenic activities (e.g. high adjacent population density, upstream pollution from urban, industrial, and/or farming activities). Soils need not be a specific type, but must be of sufficient thickness and health to support a diverse suite of lush tropical vegetation and offer significant challenges to the mobility of troops and vehicles.

A6.4.C. Biological Considerations.

Given the specific climatic, topographic and geographic constraints listed above, the major biological considerations for a tropical testing site are specific tropical vegetation characteristics and the presence of a diverse community of above- and below-ground organisms. In the past, military interest in tropical vegetation was primarily based on the forest structure and distribution in both horizontal and vertical dimensions as challenges to vision, mobility, and performance of personnel and equipment. For other organisms, especially microbes, concerns focus primarily on sufficient density to produce high rates of the metabolic processes and by-products that foul materiel and interfere with equipment and systems. Military testing at present and in the future requires much greater detail and understanding of the structure, function, and interrelationships of species in complex tropical ecosystems.

The ideal tropical environment has been defined by 14 variables of climate, physical setting, and biologic conditions. Numerous studies of unique sites have been conducted by various panels since the late 1990s. This body of work (represented in Table A6-2) has greatly advanced the ability of the DoD to understand the complexities of the tropical environment and therefore how best to test in the tropics. However, this information was not readily accessible to the many organizations that would find it useful because it was dispersed in the numerous separate reports. Further, these data and analyses had not been integrated into a comparative analysis of all the studied sites to maximize the utility of tropical test design or examining training opportunities for the DoD. From this, the evolution of tropical testing to the suite of sites approach were compiled and integrated into a single document, which compares and contrasts all of the sites examined to date.

This report, ***A Technical Analysis of Locations for Tropical Testing of Army Materiel and Opportunities for Tropical Training of Army Personnel*** (February 2009), summarized the environmental characteristics of the sites found to have testing value and made a comparative analysis between the various sites. It was intended to help the testing community select the best locations for each test and provide summary environmental data for test design. The original works remain important because each of the reports contain environmental details that are critical to the testing community when they are selecting where to test.

Table A6-1: Criteria for an Ideal Tropical Test Area (King et al., 1998).

I. Climate	
Precipitation:	2 to 6 meters (m) per year, > 0.1 m in driest month
Temperature (°C):	18 minimum average, 25 to 40 average daily
Relative Humidity (%):	Mean = 75, range = 75 to 90
II. Physical Setting	
Relief:	Elevation = Sea level to 1500 m, Site relief = 150 m minimum, Slope = 0 to 60 %, coastal location with lowlands.
Surface water:	Perennial small (1 to 2 m) to medium (up to 20m) width streams, with Nominal velocities (<2.0m/s).
Soils:	Oxisols, ultisols, inceptisols, minimum depth in the range of 10m
III. Biological Considerations	
Vegetation Structure: Secondary tropical rainforest with undisturbed growth for 25 years. Closed canopy forest cover. Minimum, 70 to 95% of stems <10cm dbh with remaining stems >20cm dbh, basal area 20 to 70m^2/hectare, established understory growth. Microbiology: Diverse fauna and decomposer populations	

Table A6-2: Previous Tropical Panel Study Reports.

Report Title	Date Published	Country	Site(s)
A Technical Analysis to Identify Ideal Geographic Locations for Tropical Testing of Army Materiel and Systems	July 1998	World	14 geographic areas
A Technical Analysis of Hawai'i & Puerto Rico for Tropical Testing of Army Materiel and Systems	April 1999	USA	7 sites in Hawai'i and 4 sites in Puerto Rico
A Technical Analysis of Australia for Tropical Testing of Army Materiel and Systems	July 2001	Australia	3 sites, beach and jungle
A Technical Analysis of Suriname for Tropical Testing of Army Materiel and Systems	March 2006	Suriname	3 sites
A Technical Analysis of Cerro Tigre and Altos de Pacora, Panama, for Tropical Testing of Army Materiel Equipment and Systems	May 2006	Panama	2 sites
A Technical Analysis of Fuerte Mocoron, Honduras, for Tropical Testing of Army Materiel Equipment and Systems	September 2007	Honduras	3 sites
A Technical Analysis of Llano Carti, Panama, for Tropical Testing of Army Materiel Equipment and Systems	November 2007	Panama	1 site